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The OPERA experiment:

Direct tau neutrino appearance and neutrino time-of-flight measurement

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on behalf of the **OPERA** collaboration

OPERA

bmb+f - Förderschwerpunkt
OPERA
Großgeräte der physikalischen Grundlagenforschung

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the OPERA collaboration

~160 scientists, 30 institutes, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
LNGS Assergi
Bari
Bologna
LNF Frascati
L'Aquila
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

additional contribution for neutrino velocity measurement:
CERN: CNGS, survey, timing and PS groups
PTB (National metrology institute, Germany)
METAS (National metrology institute, Switzerland)
Università Sapienza (Rome University (Italy)): Geodesy group

overview

- neutrino oscillations
- the OPERA experiment
  - the CNGS neutrino beam
  - the OPERA detector
- direct tau neutrino appearance
- summary

- neutrino time-of-flight measurement
- statement

neutrino oscillations

- creation as weak flavor eigenstate

$$|\nu\rangle = \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix}$$

- propagation as mass eigenstate

$$|\nu'\rangle = \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$|\nu'(t)\rangle = e^{-iH't}|\nu'(0)\rangle$$

Without neutrino decays, H' is real and diagonal, solution is simple!

- detection as weak flavor eigenstate

$$|\nu(t)\rangle \ ?$$

neutrino oscillations

- unitary transformation: $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i'\rangle$
- choose parametrization of U:

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

$c_{ij}=\cos(\theta_{ij})$, $s_{ij}=\sin(\theta_{ij})$, CP-violating phase δ (without Majorana phases)

- transition probability:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

$$\left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/(2E)} \right|^2$$

neutrino oscillations

- measure entries of U:
  $\theta_{12} \approx 34°$, $\theta_{13} \approx 0°$, $\theta_{23} \approx 45°$, δ_{CP}=???

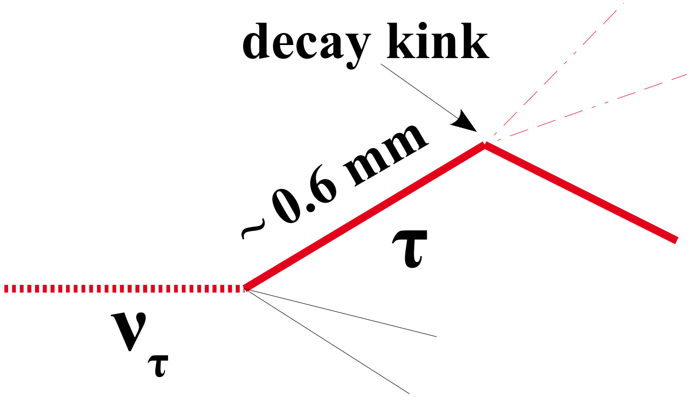
- measure mass differences: $\Delta m_{12}^2 \approx 8\times10^{-5} eV^2$
  $|\Delta m_{13}^2| \approx |\Delta m_{23}^2| \approx 2.5\times10^{-3} eV^2$

- this simplifies things for OPERA:

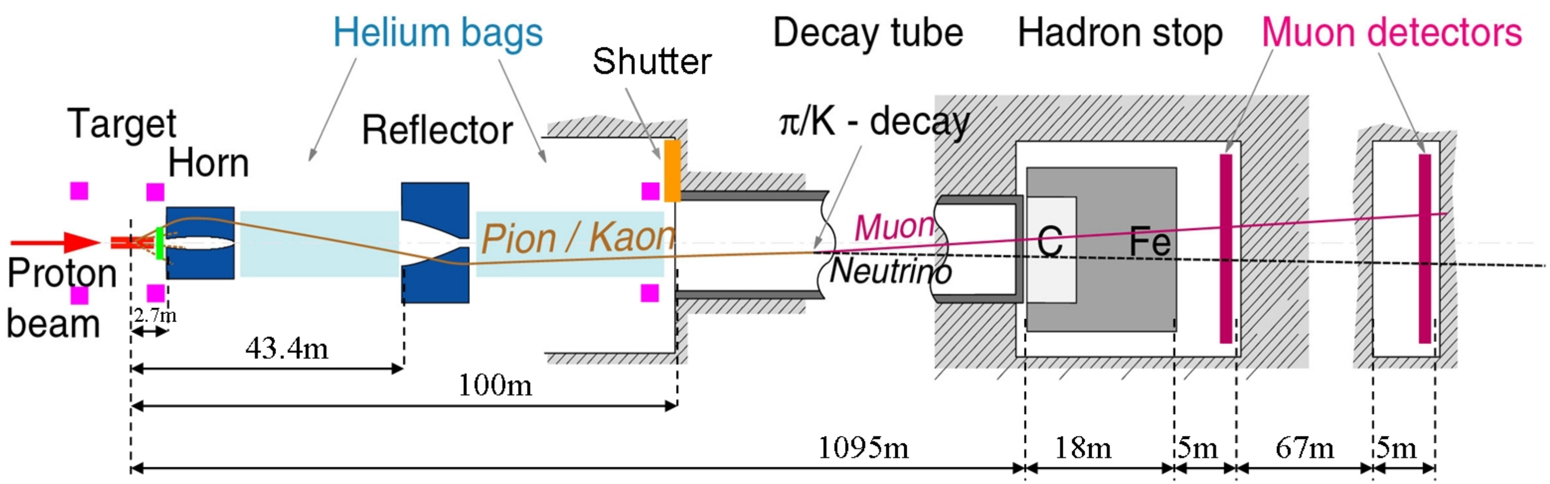
$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

the OPERA experiment

- main physics goal:
  - first direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations
- concept:
  - long baseline ν_μ beam, E_ν» $E_{thresh}(CC\ \nu_\tau)$=3.5GeV
  - event-by-event detection of τ leptons
- requirements:
  - high target mass (~1000t)
  - high spacial resolution (~1µm)
  - very low background rate



the CNGS neutrino beam



$\langle E_{\nu_\mu} \rangle$	$17\,\mathrm{GeV}$
$\bar{\nu}_\mu/\nu_\mu$	$2.4\,\%$ (CC interactions)
ν_e/ν_μ	$0.89\,\%$ (CC interactions)
$\bar{\nu}_e/\nu_\mu$	$0.06\,\%$ (CC interactions)
ν_τ/ν_μ	$< 10^{-4}\,\%$ (CC interactions)

about 2.1×10^{13} POT per extraction, 2 extractions per SPS filling

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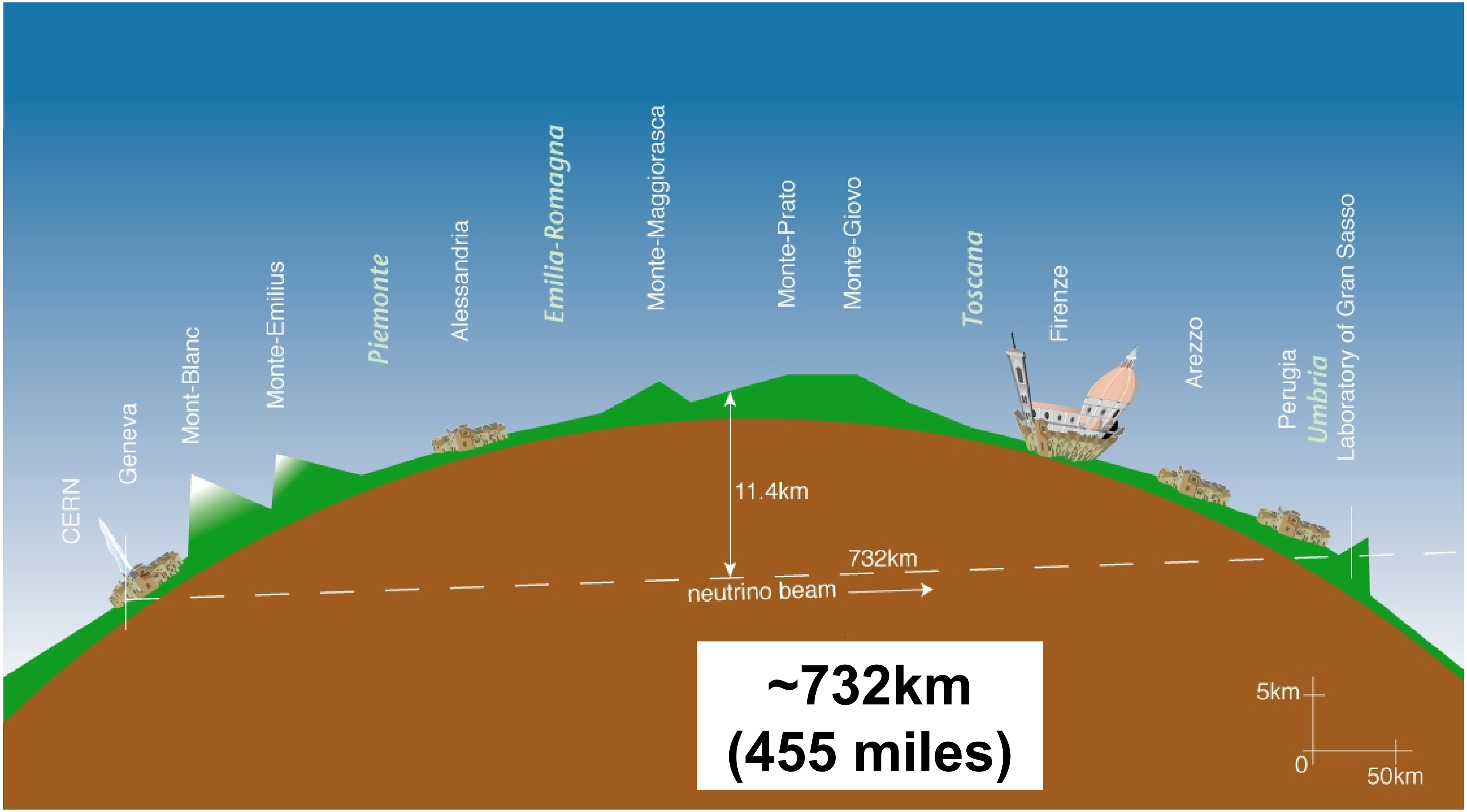
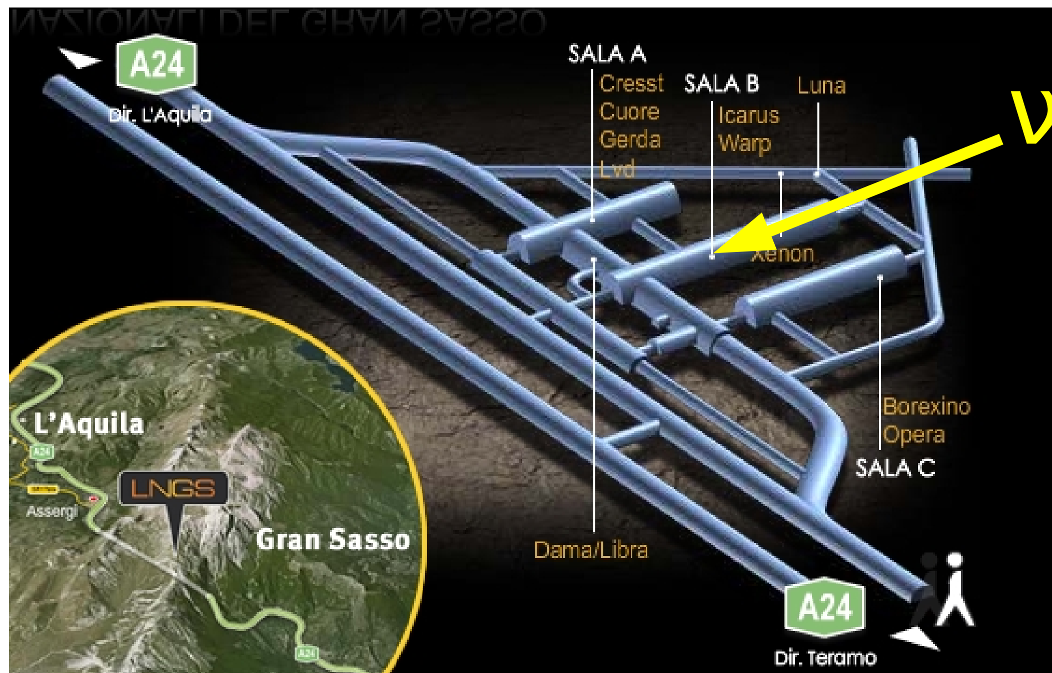
neutrino propagation



~732km
(455 miles)

neutrino propagation

- LNGS underground lab
  - under 1400m rock (3800mwe)
  - highway access



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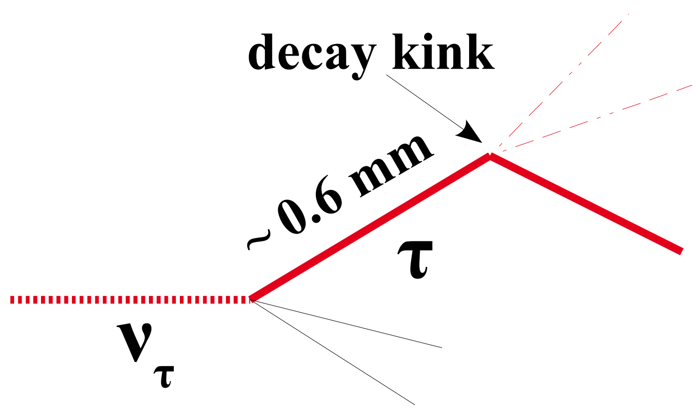
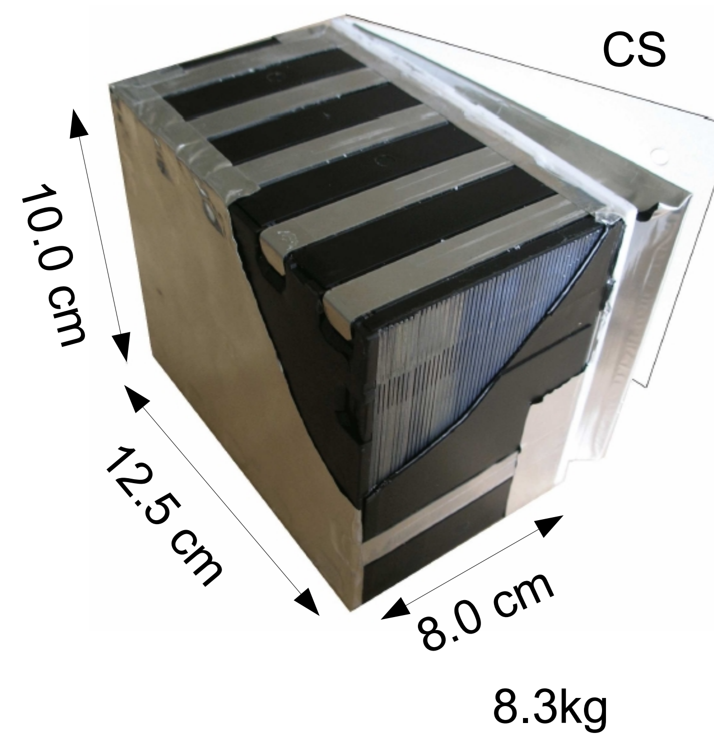
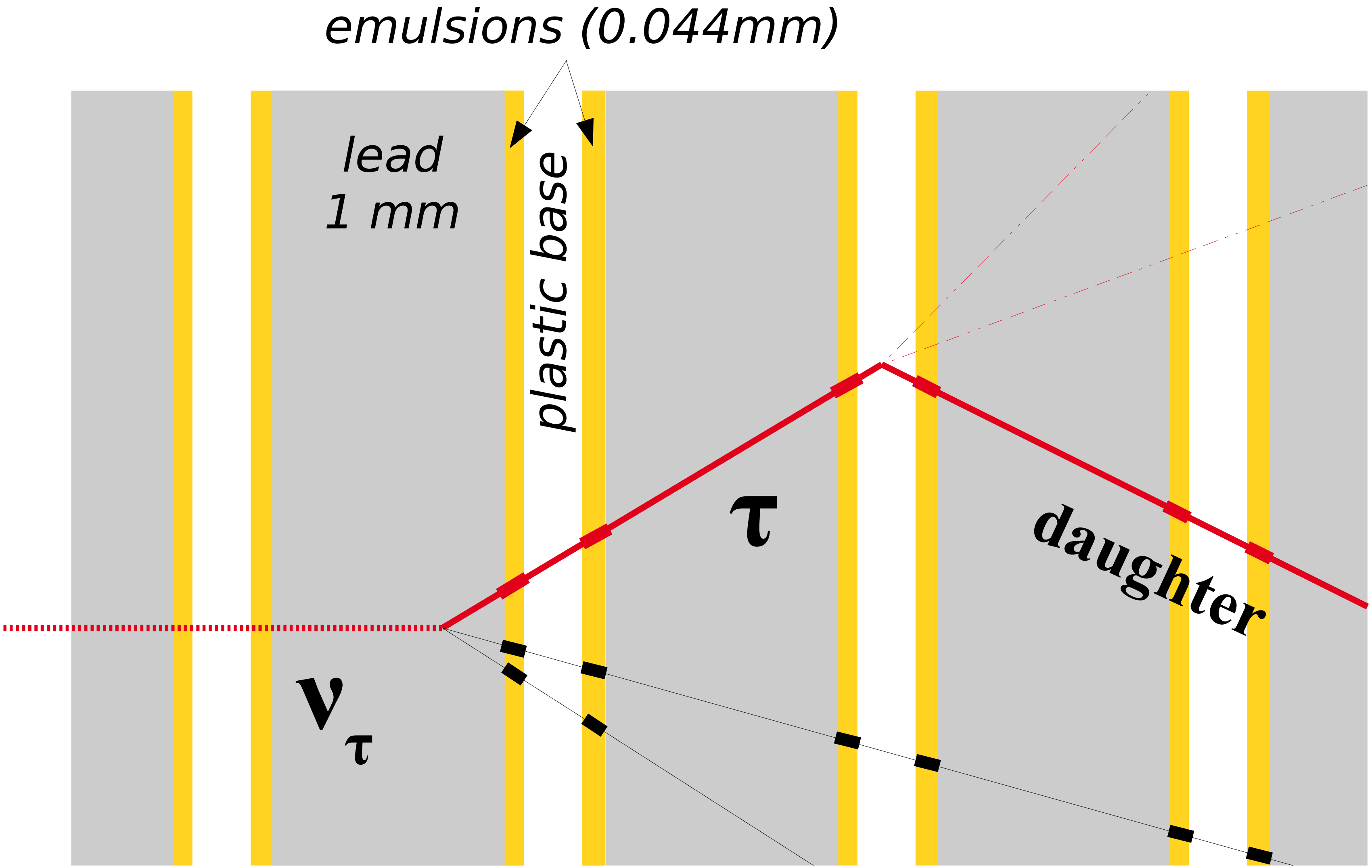
the OPERA detector

- bricks (emulsion cloud chamber (ECC))
  - 57 emulsion films (0.2mm, plastic base+emulsion coating)
  - 56 lead plates (1mm)
  - two changeable sheets (CS) per brick
- brick features
  - spatial resolution (vertex): ~1µm
  - angular resolution (track): ~2mrad
  - scaleable → 150,000 bricks in total





the OPERA detector



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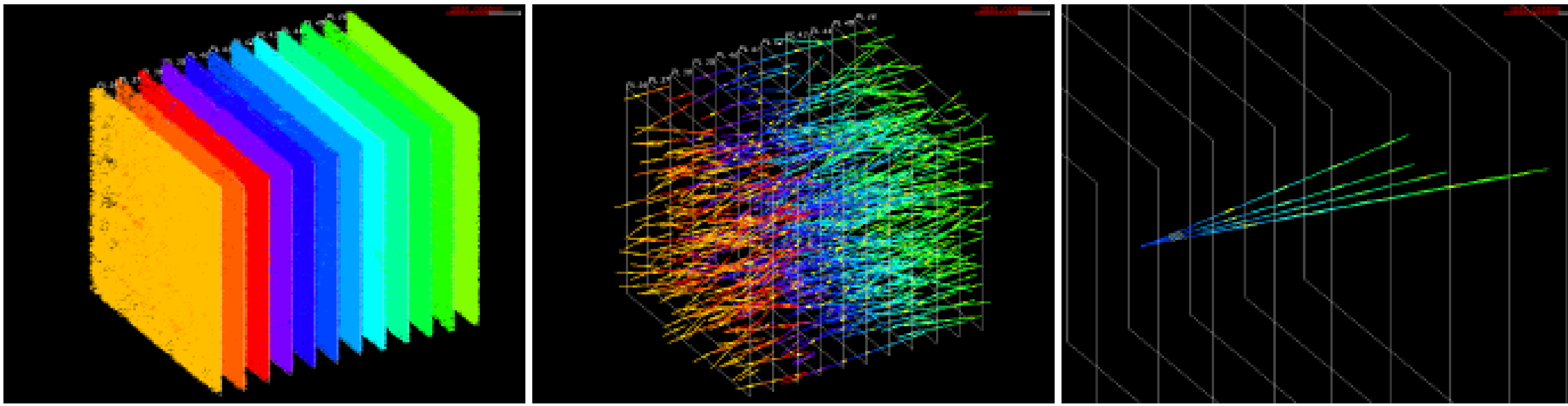
the OPERA detector

radioactivity, cosmics, ... | only tracks | vertex



- emulsions are scanned by optical microscopes
  - follow tracks predicted by CS, reconstruct 3D tracks
  - search for possible vertices, scan in ~$1 cm^3$ volume
  - kinematical analysis, EM-shower reconstruction

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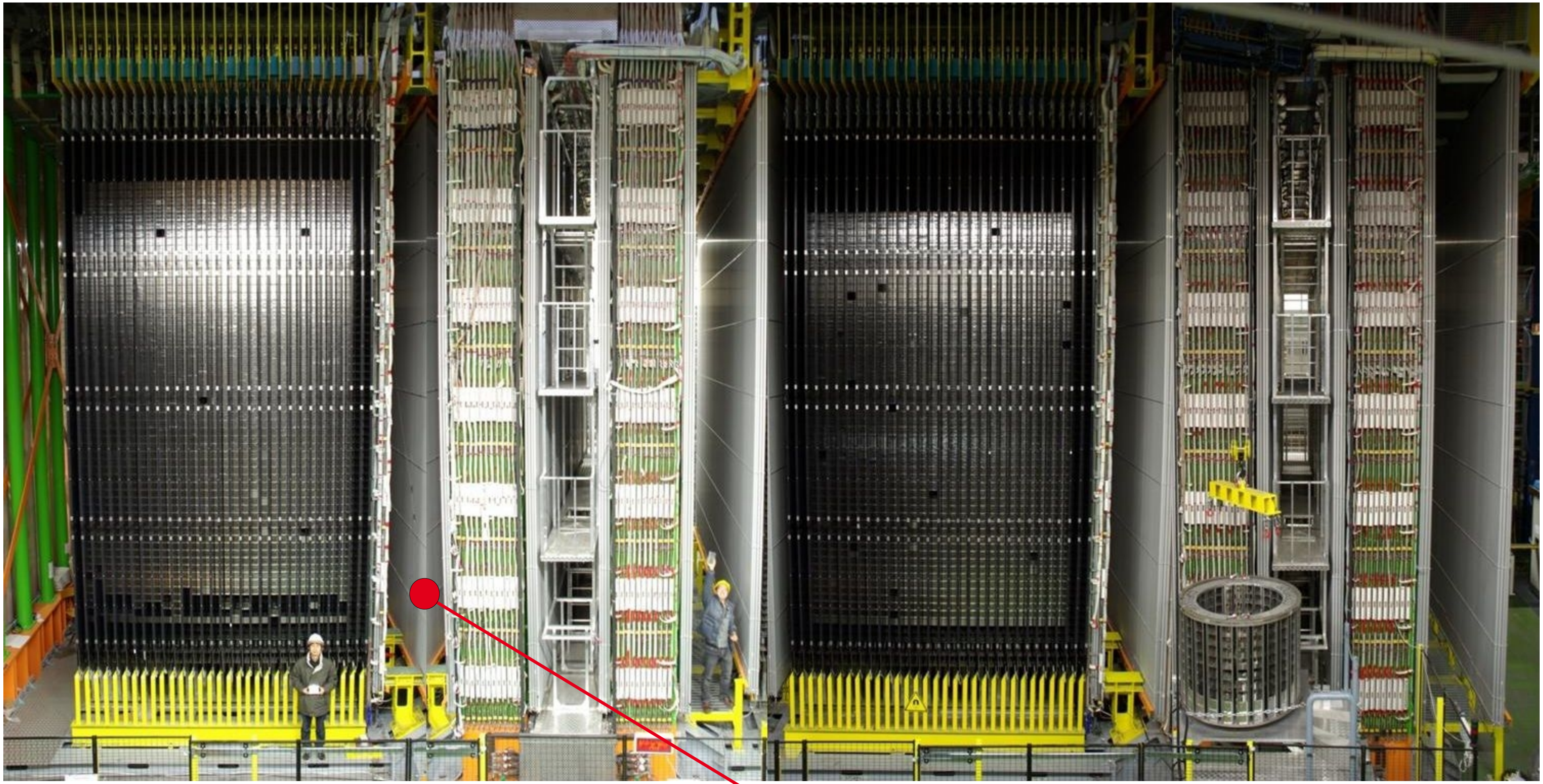
the OPERA detector

- ECC have limitations, though:
  - passive, non-electronic – how to find the correct brick?
  - cannot measure particle charge, muon/hadron separation
  - too small for calorimetric (hadr.) shower measurement

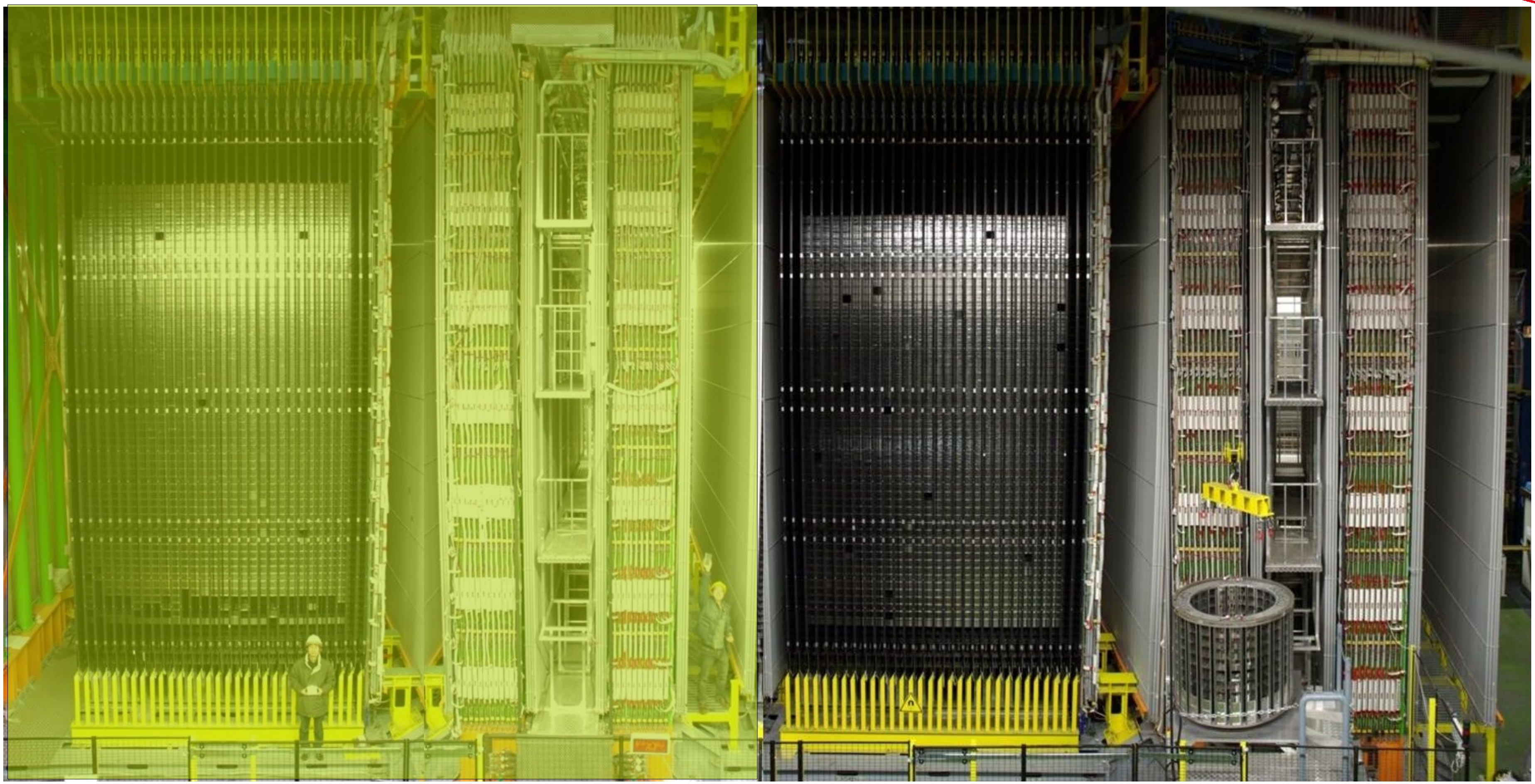
the OPERA detector



neutrinos

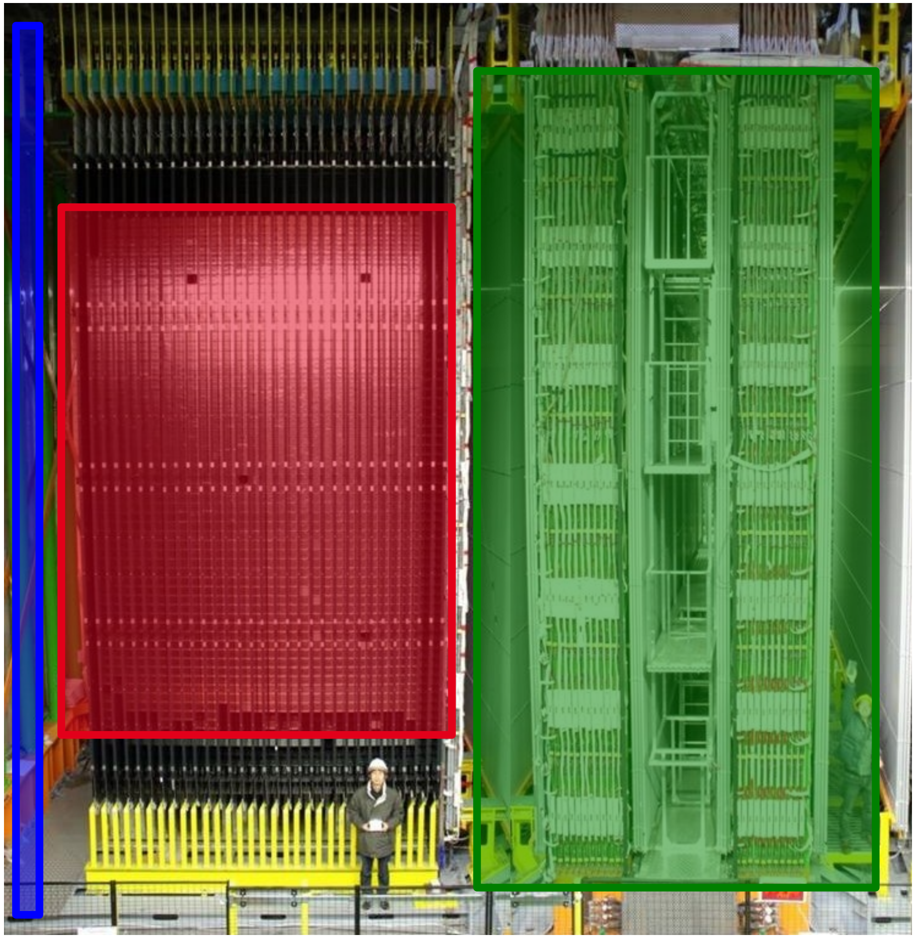
need that later: “OPERA reference point A1”

the OPERA detector



super module 1 super module 2

the OPERA detector



super module 1

veto (only SM1)
RPC

target section
75,000 ECC bricks per SM
31 pairs of planes of
horiz. and vert. plastic
scintillator strips

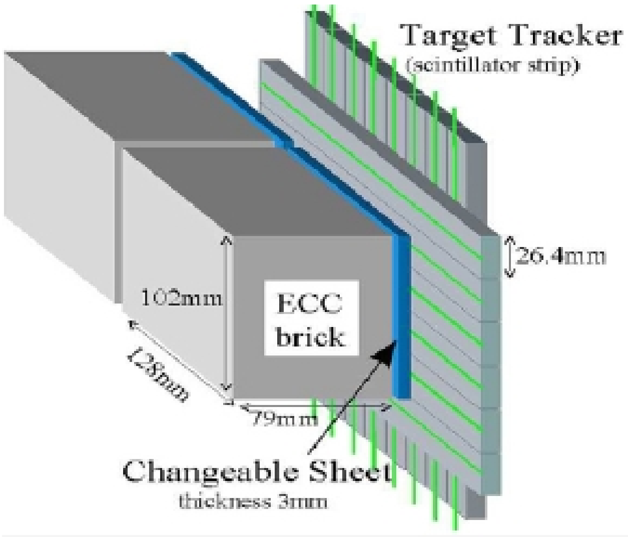
spectrometer
1.5T dipole magnet
RPC inner trackers
drift tubes

target section

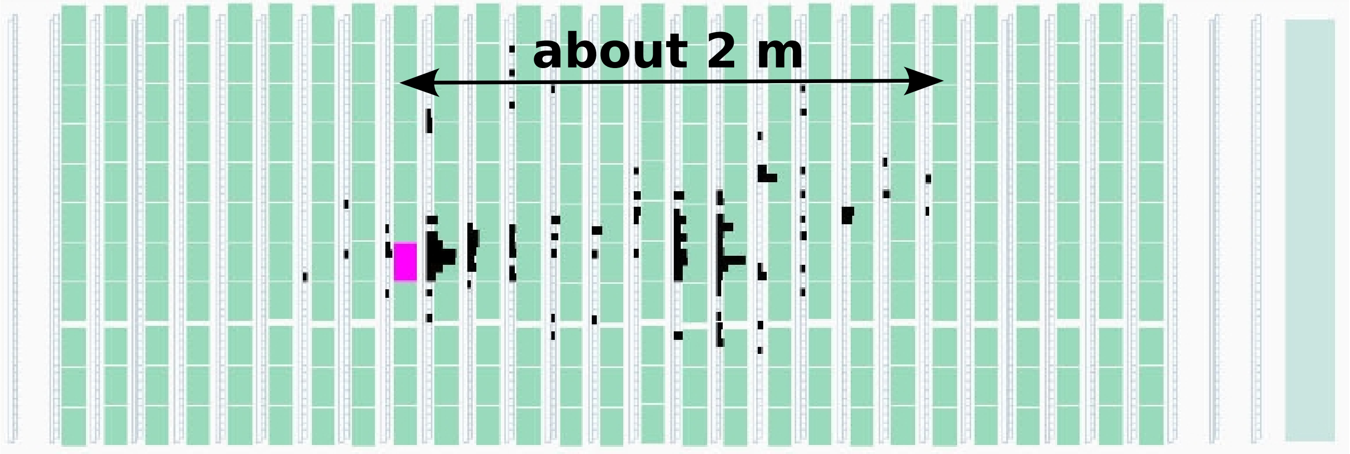
- 31 walls per SM
  - lead/emulsion ECC
  - CS
  - horizontal scintillator strips
  - vertical scintillator strips

lead/emulsion ECC, CS: passive, excellent spatial/angular resolution

horizontal/vertical scintillator strips: active, excellent time resolution (~1ns), spatial resolution ~1cm

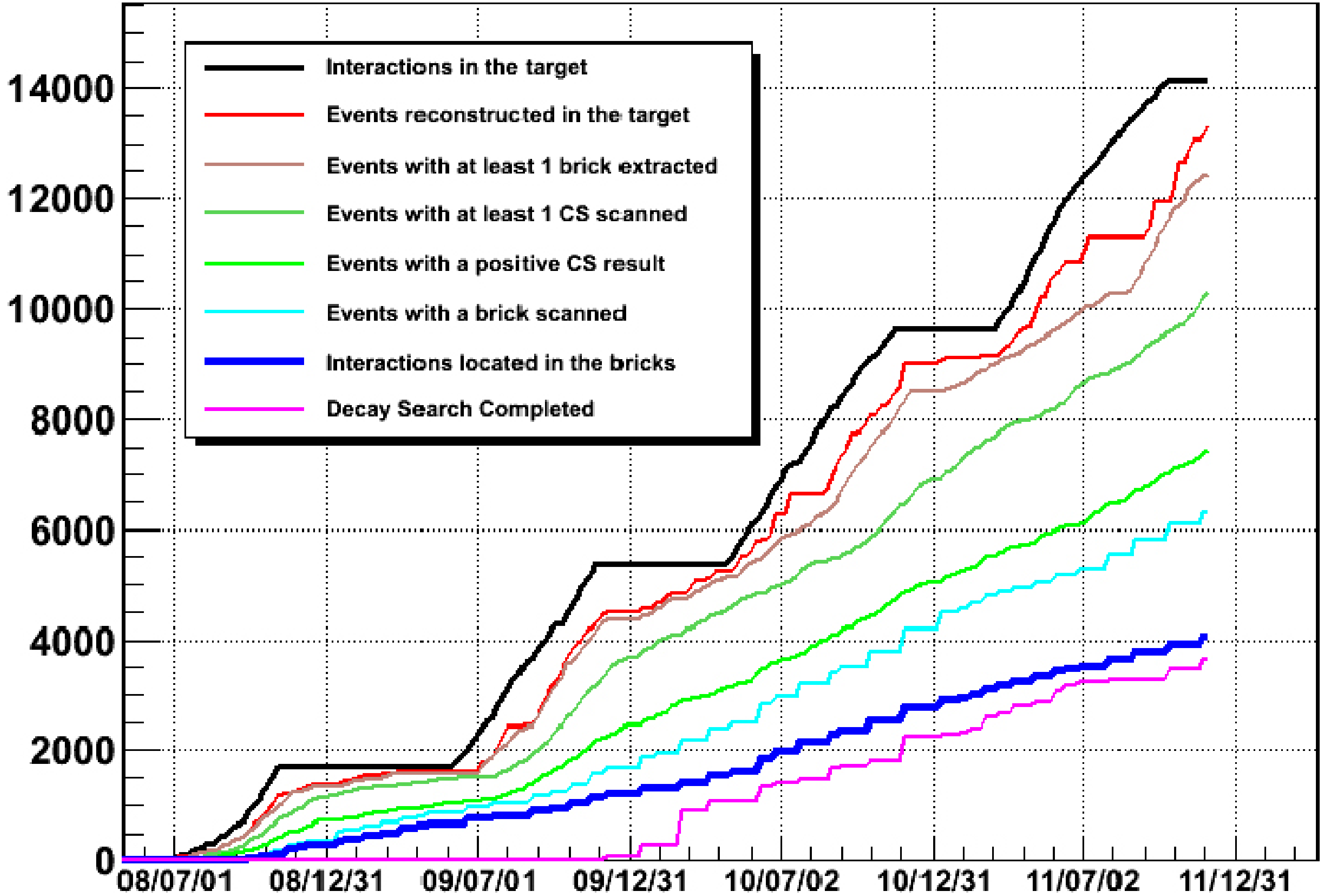


search procedure



- the typical procedure (shortened)
  - use scintillators as trigger and to predict **neutrino vertex brick**
  - extract that predicted brick using robots
  - take CS from that brick, leave brick underground
  - compare TT track predictions and CS tracks - if they match:
  - scan brick following CS predicted tracks
  - found vertex? search for a decay...

search procedure status



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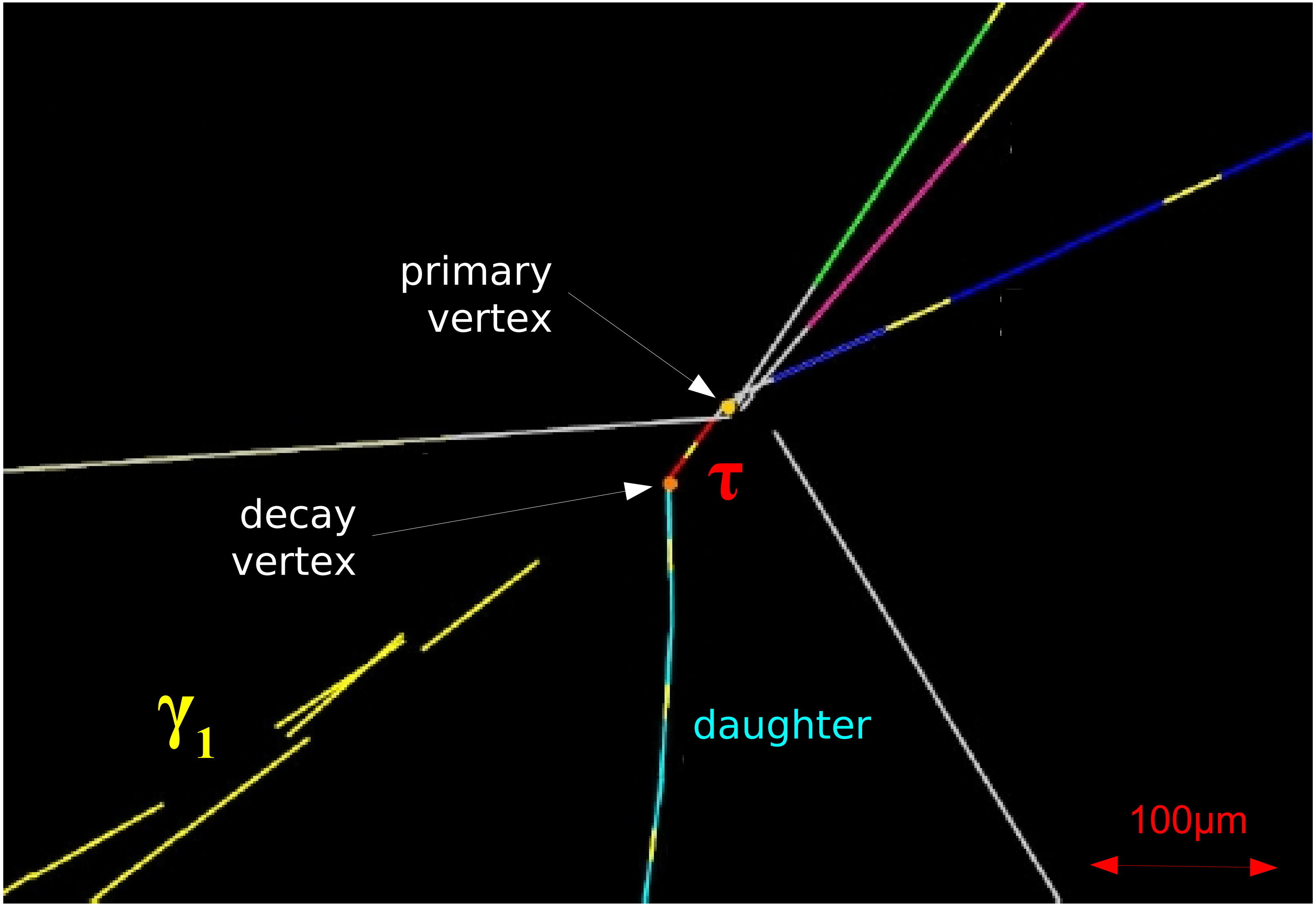
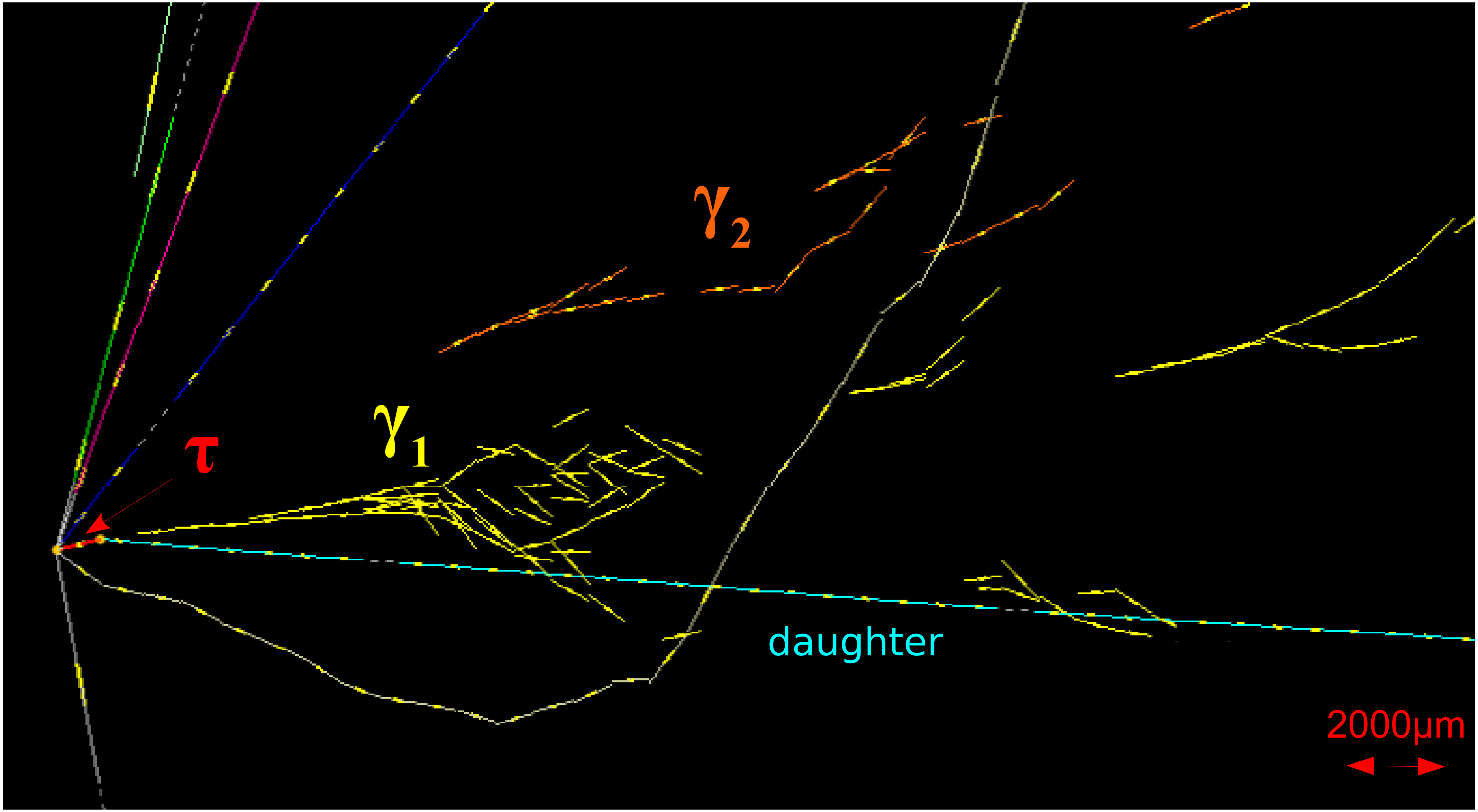
the first tau candiate

tau candidate event (1)



tau candidate event (2)



selection cuts, tau candidate

Variable	Cut-off	Value
Missing P_T at primary vertex (GeV/c)	<1.0	$0.57^{+0.32}_{-0.17}$
Angle between parent track and primary hadronic shower in the transverse plane (rad)	$> \pi/2$	3.01 ± 0.03
Kink angle (mrad)	>20	41 ± 2
Daughter momentum (GeV/c)	>2	12^{+6}_{-3}
Daughter P_T when γ-ray at the decay vertex (GeV/c)	>0.3	$0.47^{+0.24}_{-0.12}$
Decay length (μm)	<2 lead plates	1335 ± 35

kinematical analysis, tau cand.

kinematical analysis:

- two EM showers (γ_1 and γ_2) pointing towards decay vertex, invariant mass: (120 ± 20(stat.) ± 35(syst.))MeV/c²

  hypothesis: $\pi^0 \rightarrow \gamma\gamma$ ($m_{\pi 0}$=135MeV/c²)

- daughter is a charged hadron, most likely a charged pion, invariant mass (π+2γ): $(640^{+125}_{-80}\,(\text{stat.})^{+100}_{-90}\,(\text{syst.}))\,\text{MeV}/c^2$

  hypothesis: $\rho^- \rightarrow \pi^0 \pi^-$ ($m_{\rho-}$=770MeV/c²)

- single-prong hadronic tau decay

  hypothesis: $\tau^- \rightarrow \rho^- + \nu_\tau$ (B.R. ~25%)

  $\rho^- \rightarrow \pi^0 + \pi^-$

  $\pi^0 \rightarrow \gamma\gamma$

tau background and efficiency

Decay channel	Number of background events expected for							
	22.5×10^{19} p.o.t.				4.88×10^{19} p.o.t.			
	Charm	Hadron	Muon	Total	Charm	Hadron	Muon	Total
$\tau \to \mu$	0.025	0.00	0.07	0.09 ± 0.04	0.00	0.00	0.02	0.02 ± 0.01
$\tau \to e$	0.22	0.00	0.00	0.22 ± 0.05	0.05	0.00	0.00	0.05 ± 0.01
$\tau \to h$	0.14	0.11	0.00	0.24 ± 0.06	0.03	0.02	0.00	0.05 ± 0.01
$\tau \to 3h$	0.18	0.00	0.00	0.18 ± 0.04	0.04	0.00	0.00	0.04 ± 0.01
Total	0.55	0.11	0.07	0.73 ± 0.15	0.12	0.02	0.02	0.16 ± 0.03

Decay channel	Number of signal events expected for		Interaction vertex location efficiency	Global τ detection efficiency
	22.5×10^{19} p.o.t.	4.88×10^{19} p.o.t.		
$\tau \to \mu$	1.79	0.39	0.54	0.09
$\tau \to e$	2.89	0.63	0.59	0.14
$\tau \to h$	2.25	0.49	0.59	0.04
$\tau \to 3h$	0.71	0.15	0.64	0.04
Total	7.63	1.65	0.59	0.07

tau search summary

- We have analysed 4.88×10^{19} POT of data
- We found 1 tau candidate
- We expect a background of 0.05±0.01 events in the $\tau^- \rightarrow 1h$ channel (0.16±0.03 for $\tau \rightarrow$ any)
- p-value of the background only hypothesis is 5% (15% for $\tau^- \rightarrow$ any)
- We expect 0.49 τ candidates in the $\tau \rightarrow 1h$ channel (1.65 for $\tau \rightarrow$ any) in the analysed sample

time-of-flight measurement

(omitting most technical details)

introduction

- definition of time-of-flight (TOF)

$$TOF_\nu = t_B - t_A - \text{delays}$$

- “typical” TOF measurement principle
  - measure the neutrino production time t_A
  - measure the distance between production and detection
  - measure the neutrino detection time t_B
- definition of neutrino velocity:

$$v_\nu = \text{distance}/TOF_\nu$$

- blind analysis (delays blinded)

brief history

- 1979: FNAL *(Phys. Rev. Lett. 43 (1979) 1361)*
  - short distance, 30 GeV ν_μ, comparison of ν_μ and μ TOF
  - $|v-c|/c \leq 4\times10^{-5}$
- 1988: SN1987A *(Phys. Lett. B 201 (1988) 353)*
  - very long distance (168.000 light years), 10 MeV anti-ν_e, comparison of ν and photon arrival time (not SN mod.-dep.)
  - $|v-c|/c \leq 2\times10^{-9}$
- 2007: MINOS *(Phys. Rev. D 76 (2007) 072005)*
  - 730km distance, ~3 GeV ν_μ, near detector comparison
  - $(v-c)/c = (5.1 \pm 2.9)\times10^{-5}$
- 2011: OPERA
  - 730km distance, ~17 GeV ν_μ, proton BCT comparison

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production time t_A

- protons accelerated in SPS@CERN
- protons extracted to TT40 transfer tunnel by kicker magnets ("global t_0")
- two extractions per SPS filling separated by 50ms, each 10.5µs long, consist of thousands of 2ns-long "bunches"
- proton distribution after kicker measured by fast beam current transformer (BFCT) and read-out by a waveform digitizer (WFD)
- protons focused on graphite target

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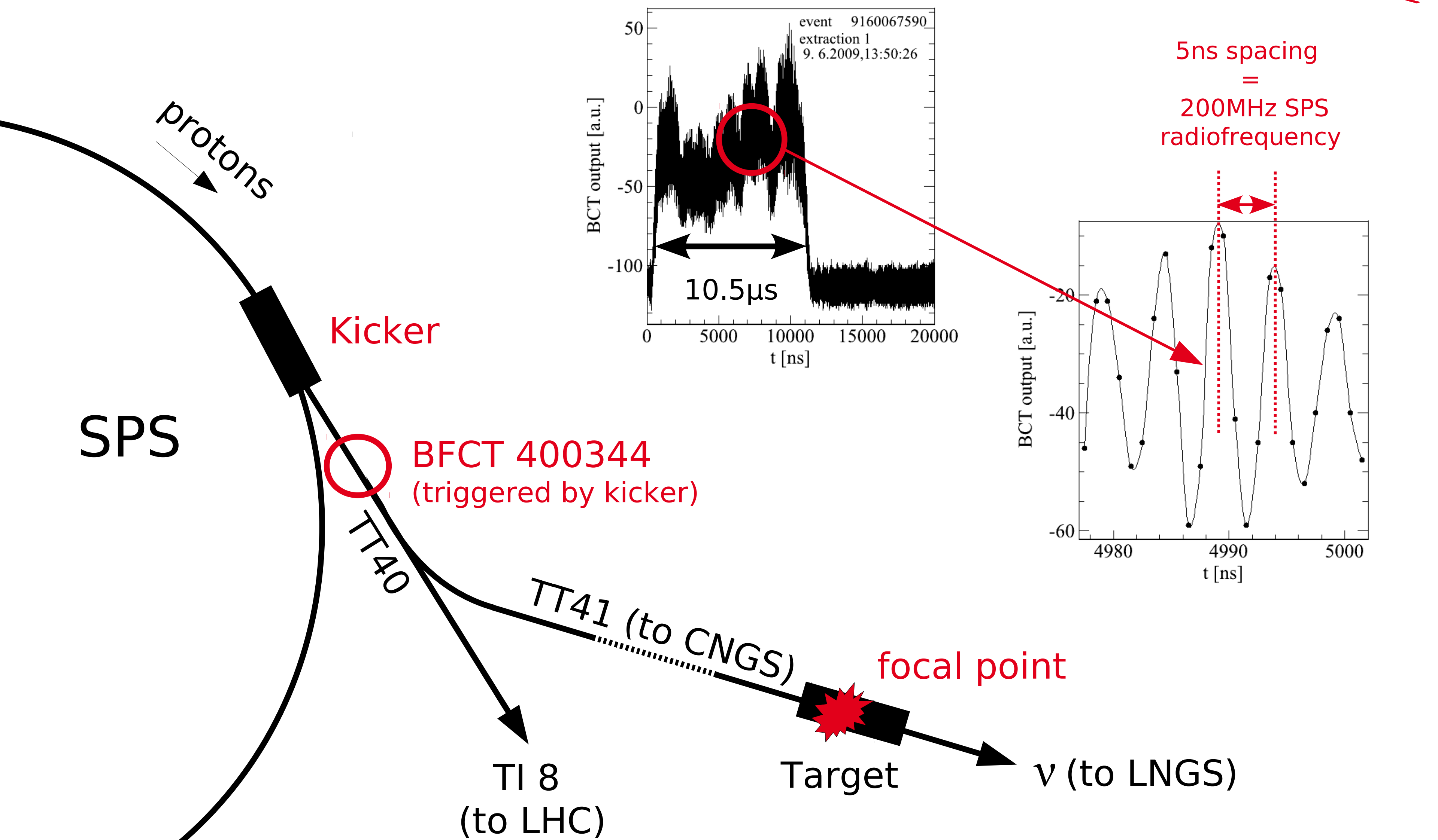
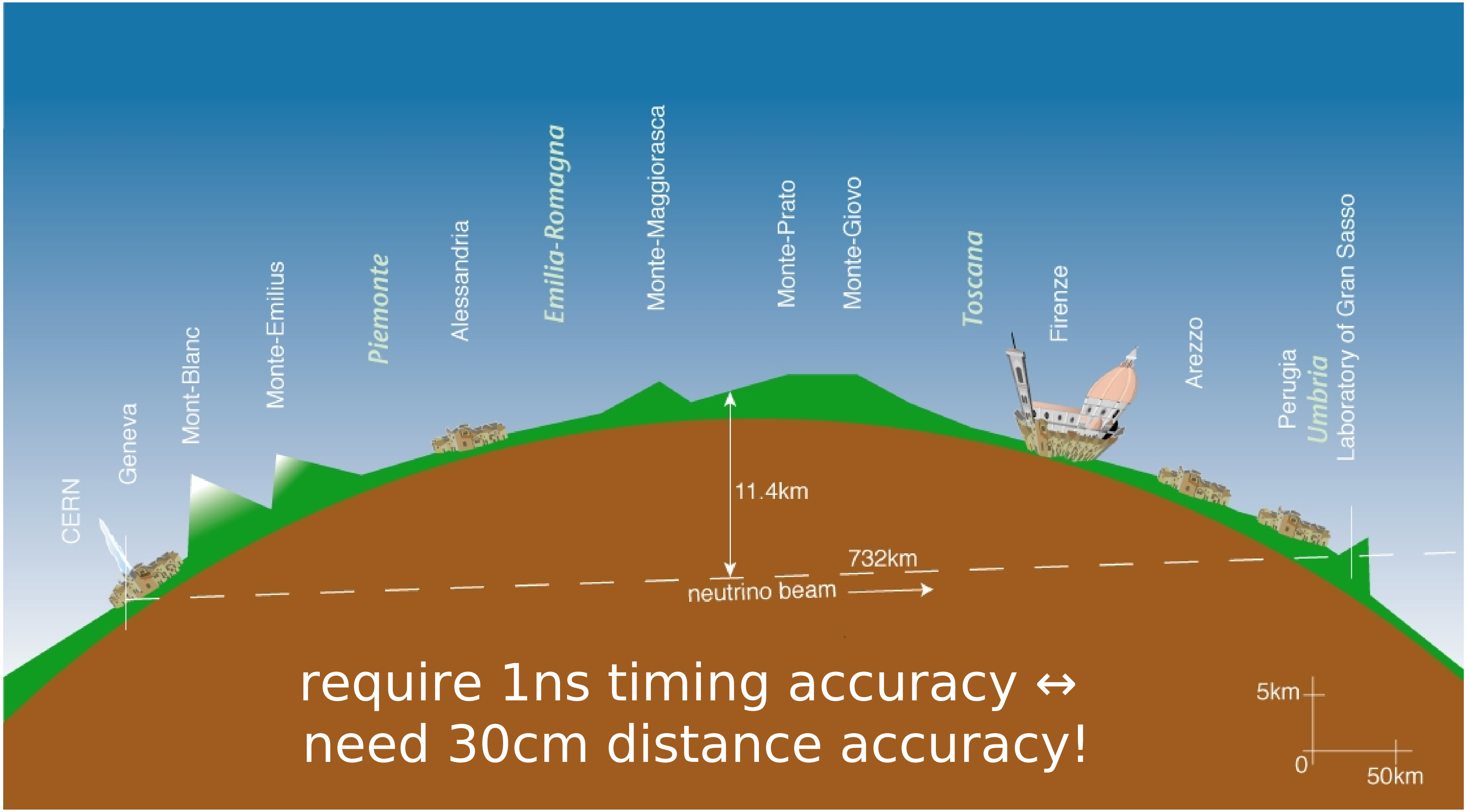
production time t_A



distance measurement



require 1ns timing accuracy ↔ need 30cm distance accuracy!

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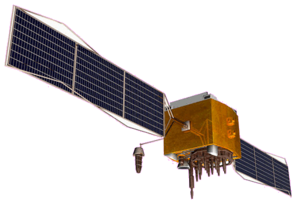
distance measurement

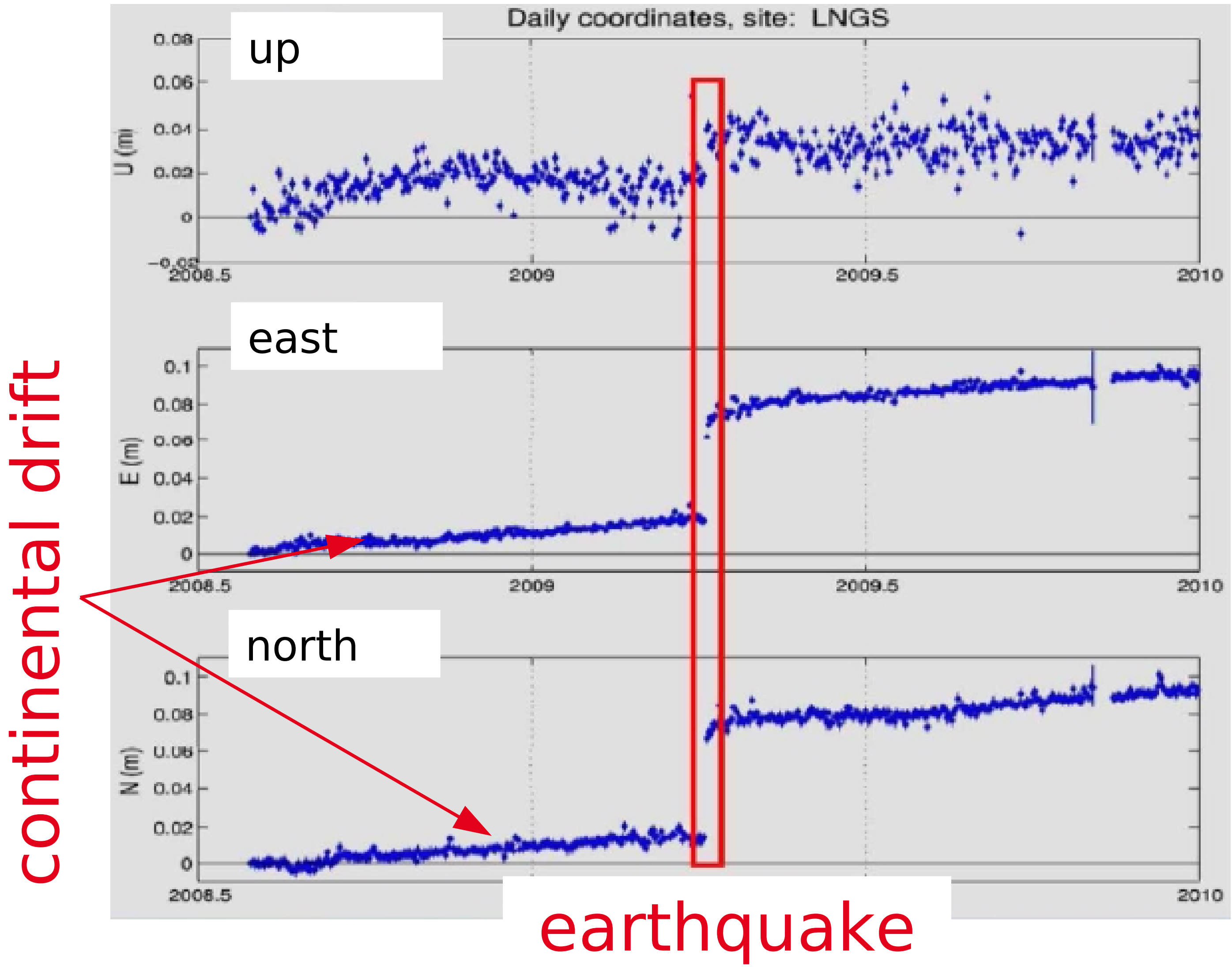
- CERN ↔ LNGS above-ground: GPS
  - establish new GPS benchmarks on both sides of the 10km highway tunnel
  - measure reference GPS points at CERN and LNGS (2010)
  - cross-checked CERN and LNGS reference points (June 2011)
- LNGS ↔ OPERA underground: optical
  - block traffic (partially*) on highway, use theodolites

    (* reason for "bad" accuracy of only 0.2m)



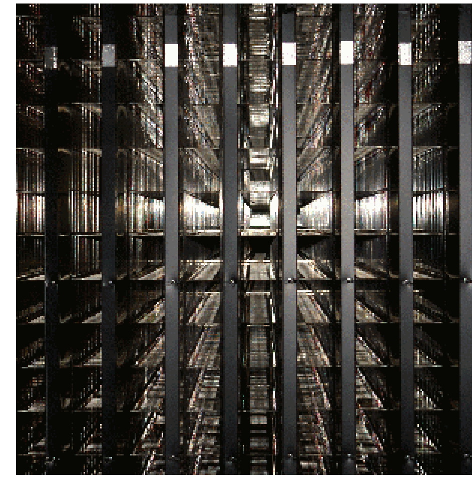
$$d(OPERA_{A1}\text{-}CERN_{BCT}) = (731278.0 \pm 0.2)\ m$$

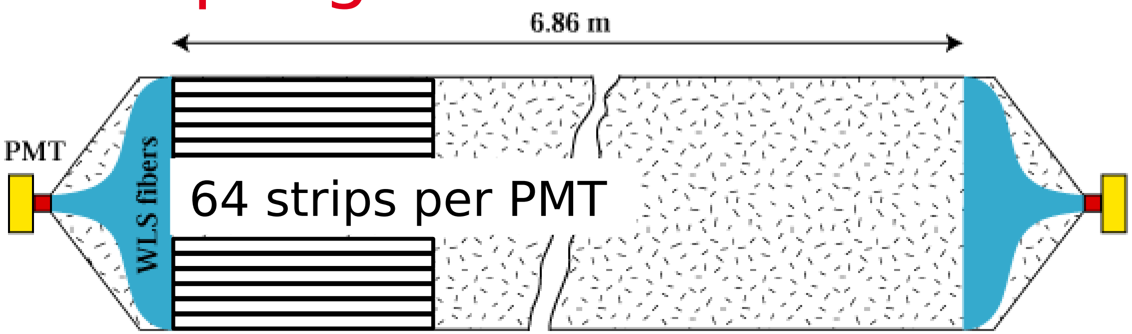
LNGS position monitoring

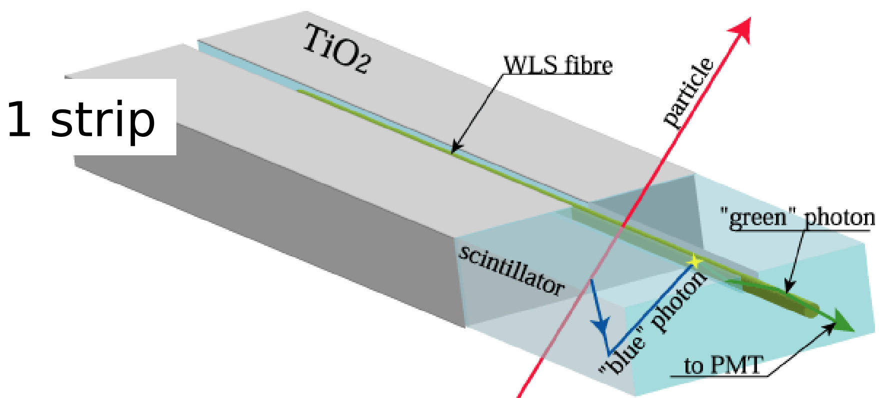


neutrino detection time t_B

- use plastic scintillators only
- first hit in target trackers is the stop signal





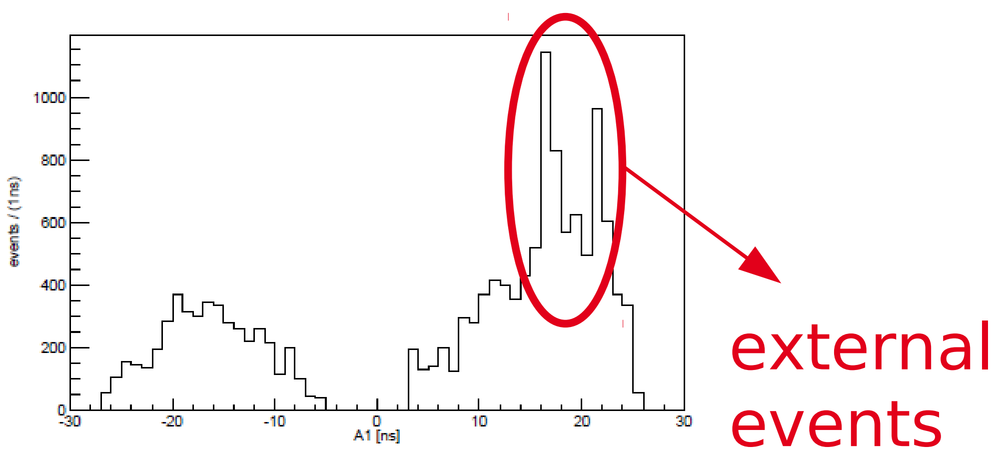


neutrino detection time t_B

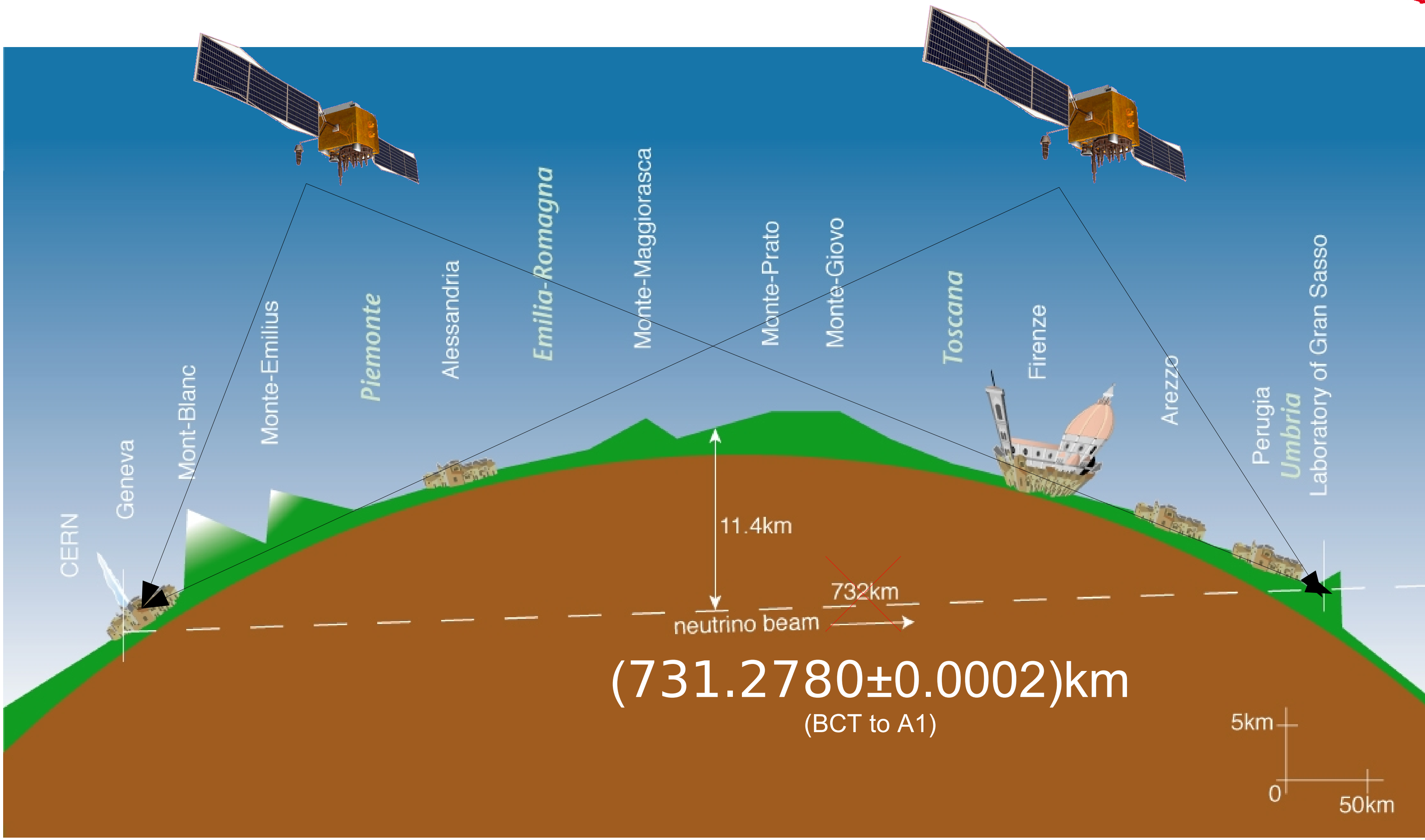
- detector-related corrections:
  - PMT → analog FE → DAQ/FPGA: (50.2 ± 2.3)ns
  - (unknown) unknown transverse hit position along the scintillator strip and pulse height effects

total: (59.6 ± 3.8)ns

- correct first hit position relative to A1 reference point (event-by-event)



clock synchronization



clock synchronization

- identical system of GPS receivers and Cs clocks at CERN and LNGS
- use GPS “common view”: the same satellites seen by receivers at CERN and LNGS
- dual-frequency GPS, “ionosphere-free” P3 code
- locations at CERN and LNGS known with high accuracy
- calibrated by METAS, cross-checked by PTB
- establish “time-link” dt~1ns

event selection

- selection of neutrino events
  - internal events (within fiducial volume, same as for the oscillation search): 7586
  - external events (interactions in rock) with reconstructed 3D muon track: 8525 (±2ns additional uncertainty)
  - at least 4 satellites in common view
  - first hit not isolated in time or space

→ 7235 internal and 7988 external events

- if neutrino event passes selection:
  select the corresponding BCT waveform

analysis

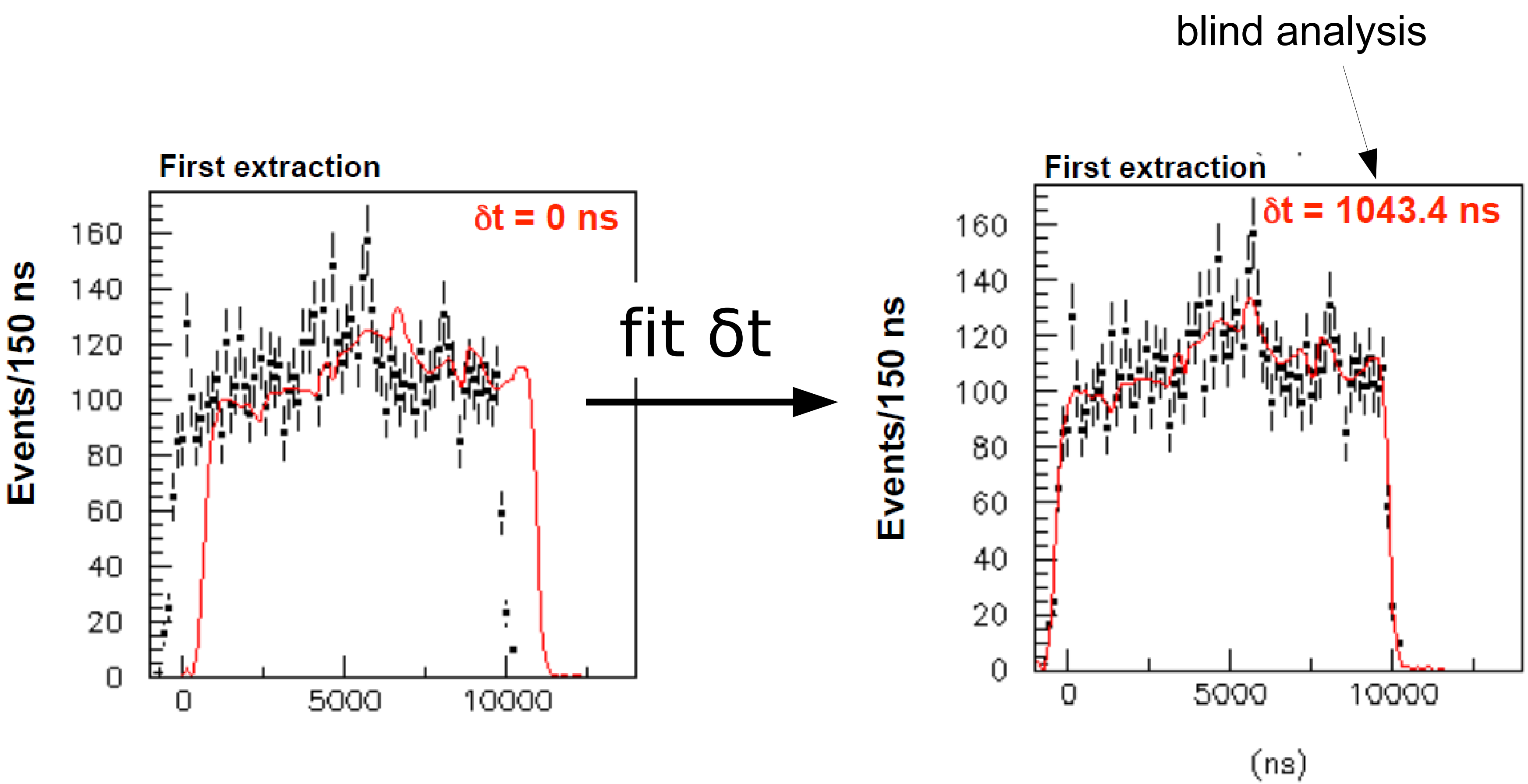
- original method:
  build likelihood from summed waveforms

$$\mathrm{L}_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \quad k = 1,2 \text{ extractions}$$

- alternative method:
  build likelihood from single waveforms,
  (smaller stat. uncertainty, additional syst. uncertainty):

$$\mathrm{L}(\delta t) = \prod_j w_j(t_j + \delta t)$$

analysis



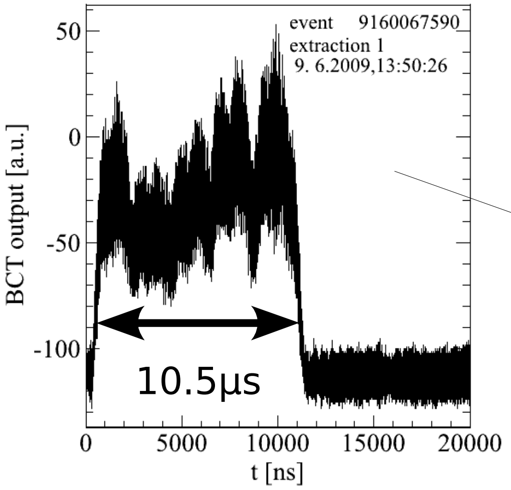
the red curve is for visualization only!

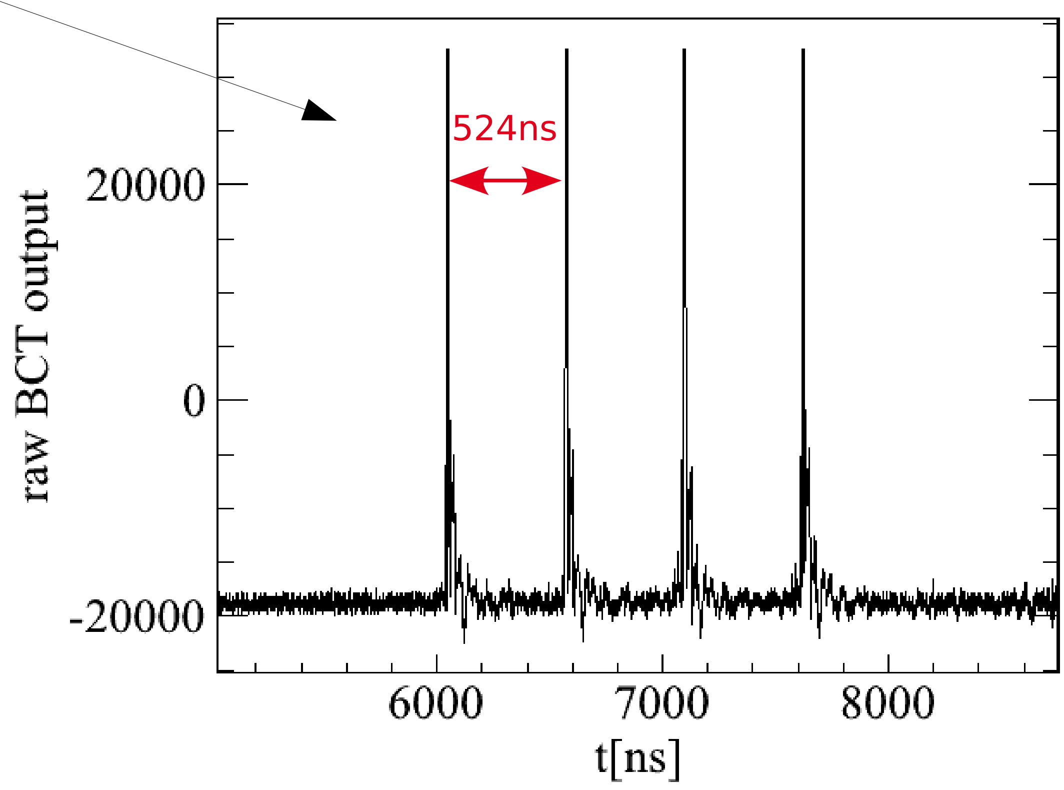
bunched beam (1)

- bunched beam: instead of 10.5μs extractions:
  4 single, 3ns-wide bunches, separated by 524ns
  → single-event TOF measurement!
- October 22 to November 6, 2011
- beam intensity lower than nominal (~1/60)
- collected 35 events, same selection criteria, same delay corrections

→ 14 external and 6 internal events

bunched beam (2)





TOF summary

- time difference $\delta t = TOF_c - TOF_\nu$:
  - original: $(57.8 \pm 7.8\ (stat.)\ ^{+8.3}_{-5.9}(sys.))$ ns
  - alternative: $(54.5 \pm 5.0\ (stat.)\ ^{+9.6}_{-7.2}(sys.))$ ns
  - bunched: $(62.1 \pm 3.7\ (stat.)\ ^{+8.3}_{-5.9}(sys.))$ ns

under investigation

- → PRESS RELEASE

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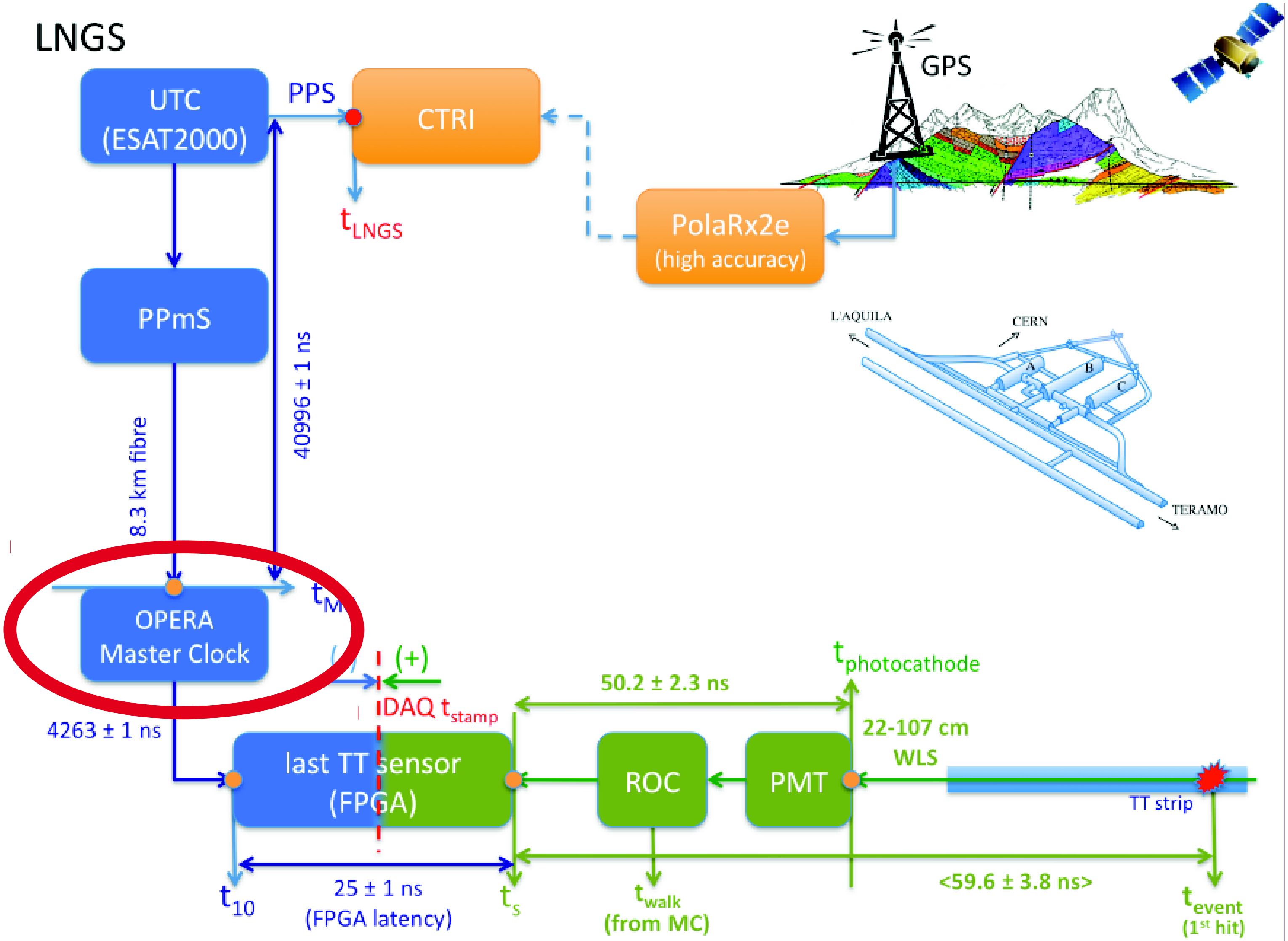
OPERA statement

"The OPERA Collaboration, by continuing its campaign of verifications on the neutrino velocity measurement, has identified two issues that could significantly affect the reported result. The first one is linked to the oscillator used to produce the events time-stamps in between the GPS synchronizations. The second point is related to the connection of the optical fiber bringing the external GPS signal to the OPERA master clock.

These two issues can modify the neutrino time of flight in opposite directions. While continuing our investigations, in order to unambiguously quantify the effect on the observed result, the Collaboration is looking forward to performing a new measurement of the neutrino velocity as soon as a new bunched beam will be available in 2012. An extensive report on the above mentioned verifications and results will be shortly made available to the scientific committees and agencies." (Feb. 23rd 2012)

LNGS timing


LNGS
UTC
(ESAT2000)
PPS
CTRI
GPS
t_LNGS
PolaRx2e
(high accuracy)
PPmS
40996 ± 1 ns
8.3 km fibre
L'AQUILA
CERN
A
B
C
TERAMO
OPERA
Master Clock
(+)
DAQ t_stamp
t_photocathode
50.2 ± 2.3 ns
4263 ± 1 ns
22-107 cm
WLS
last TT sensor
(FPGA)
ROC
PMT
TT strip
t_10
25 ± 1 ns
(FPGA latency)
t_s
t_walk
(from MC)
<59.6 ± 3.8 ns>
t_event
(1st hit)

TOF summary (2)

- we can exclude some suggested explanations:
  - thermal heating/displacement of the proton target (→ new simulations)
  - horn/reflector current instabilities (→ measurement)
  - statistical analysis (→ alternative fit and bunched beam)
  - effects due to the long extractions (→ bunched beam)
  - traveling clock/red shift/rotation around sun/galaxy (→ explicitely calculated, see note)
  - “Sagnac-effect”-like effect for neutrinos included

- we still value all suggestions from you!

TOF summary (3)

- we do not see (but we cannot exclude either):
  - energy dependency
  - day/night or seasonal variations
  - dependency on beam power
  - event selection dependency (internal/external)

- LNGS/CNGS outlook 2012:
  - validate all delay and distance measurements
  - get rid of OPERA master clock/DAQ quantization
  - include OPERA spectrometers in the analysis
  - use diamond detectors in CNGS muon pits (“muon PDF”)
  - plan 2-3 weeks bunched beam, inverted polarity?
  - three LNGS experiments will join: BOREXINO, ICARUS, LVD

overall summary

- OPERA is a neutrino oscillation experiment
- found 1 ν_τ candidate, while 0.05±0.01 bkgd. events were expected. The analyzed sample corresponds to about 25% of the overall data collected until end of 2012.
- two issues that could significantly affect the reported TOF result have been found. More information very soon!
- electron neutrino appearance results in 2012
- no data taking in 2013 (CERN shutdown)

Thank you!

backup

big neutrino picture

New J. Phys., 13:063004, 2011
arXiv:1108.1376

Parameter	Best fit $\pm 1\sigma$		3σ range
$\sin^2(\theta_{12})$	$0.312^{+0.017}_{-0.015}$	$(\theta_{12} \approx 34.0^\circ)$	0.27 - 0.36
$\sin^2(\theta_{13})$	$0.013^{+0.007}_{-0.005}$	$(\theta_{13} \approx 6.5^\circ)$	0.001 - 0.035
$\sin^2(\theta_{23})$	$0.52^{+0.06}_{-0.07}$	$(\theta_{23} \approx 46.1^\circ)$	0.39 - 0.64
Δm^2_{21} [10^{-5} eV^2]	$7.59^{+0.20}_{-0.18}$		7.09 - 8.19
$\lvert\Delta m^2_{31}\rvert \approx \lvert\Delta m^2_{32}\rvert$ [10^{-3} eV^2]	$2.50^{+0.09}_{-0.16}$		2.14 - 2.76
δ_{CP}	–		0 - 2π

BOREXINO, SNO, SK...

(Double)Chooz, Daya Bay, Reno

T2K, NOvA

MINOS, OPERA, ICARUS, ...

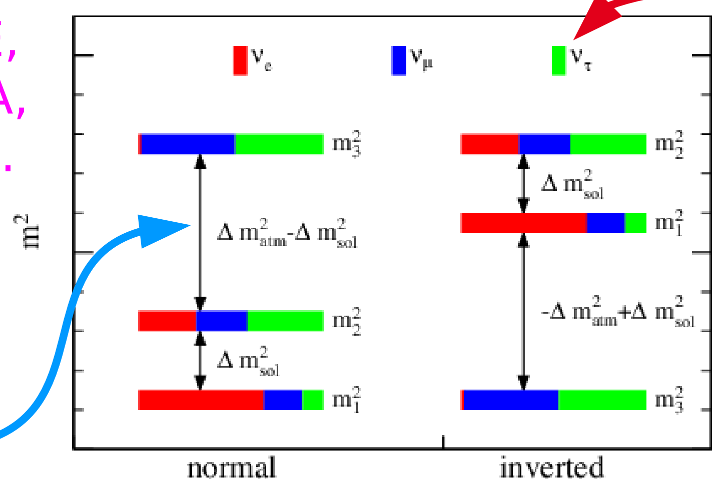
MINOS, K2K, SK, ...

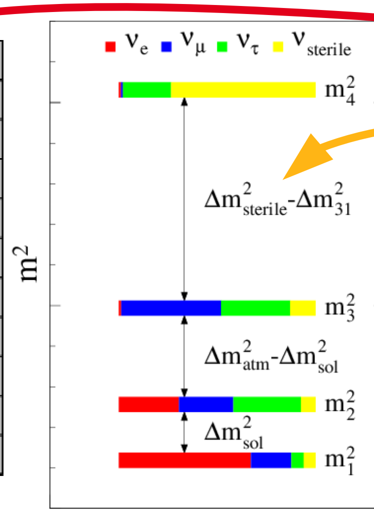
LBNE, NOvA, T2K...

NOvA,...

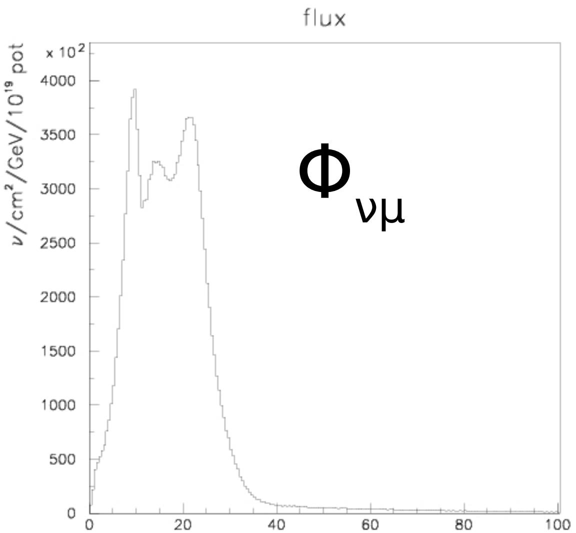
OPERA

LSND, MB, KARMEN2,...



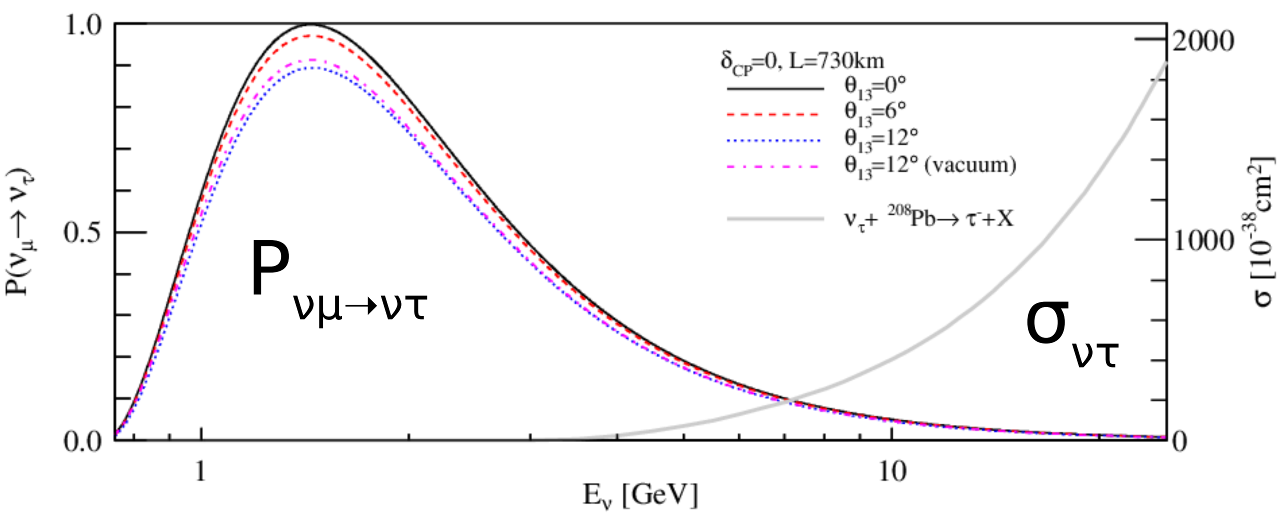


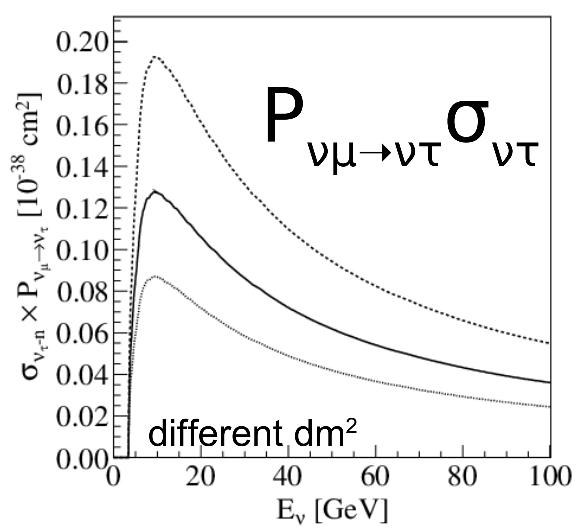
the CNGS neutrino beam



Q: Why E_{avg}=17 GeV? (compare to MINOS!)

A: $N_\tau = \int(\Phi_{\nu\mu} P_{\nu\mu\to\nu\tau}\, \sigma_{\nu\tau}\, \varepsilon_\tau)dE$





charm candidates

Topology	Observed charm candidate events	Expected events		
		Charm	Background	Total
Charged 1-prong	13	15.9	1.9	17.8
Neutral 2-prong	18	15.7	0.8	16.5
Charged 3-prong	5	5.5	0.3	5.8
Neutral 4-prong	3	2.0	<0.1	2.1
Total	39	39.1 ± 7.5	3.0 ± 0.9	42.2 ± 8.3

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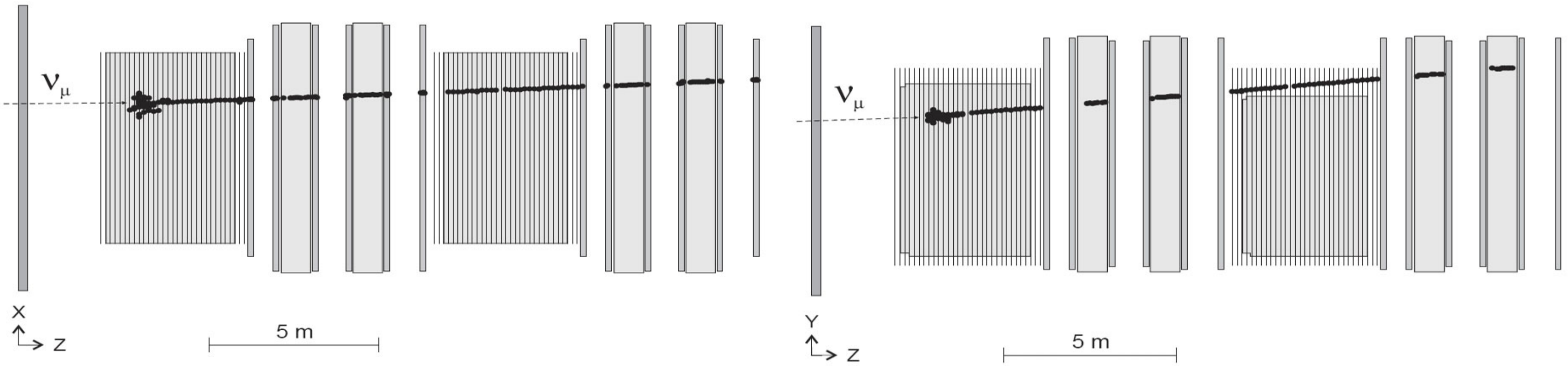
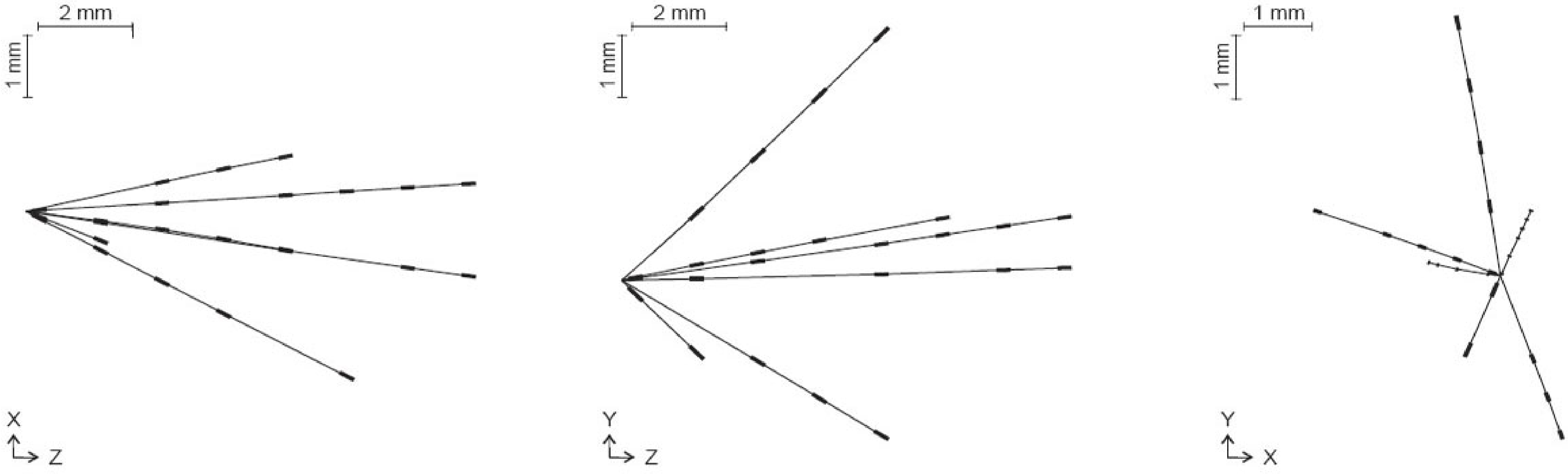
ν_μ CC event





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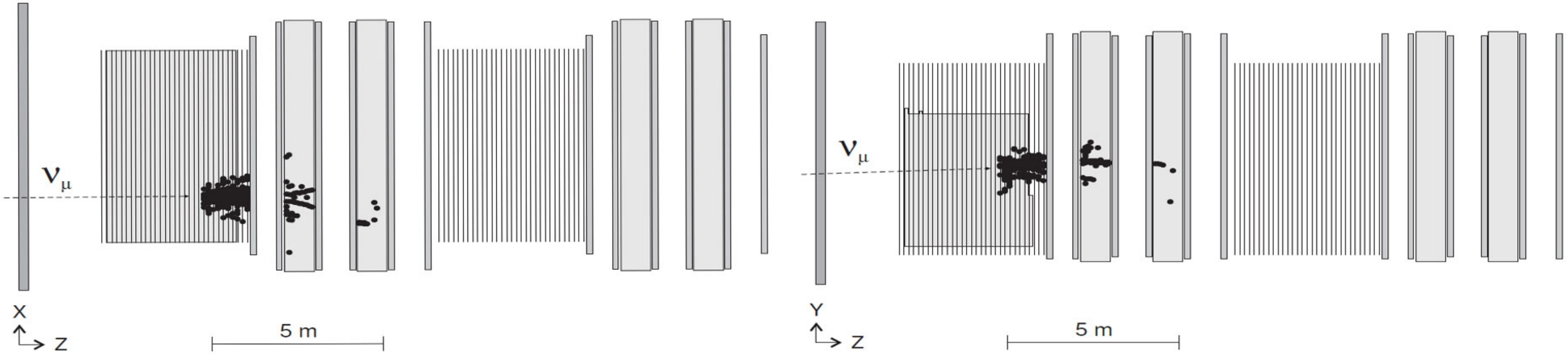
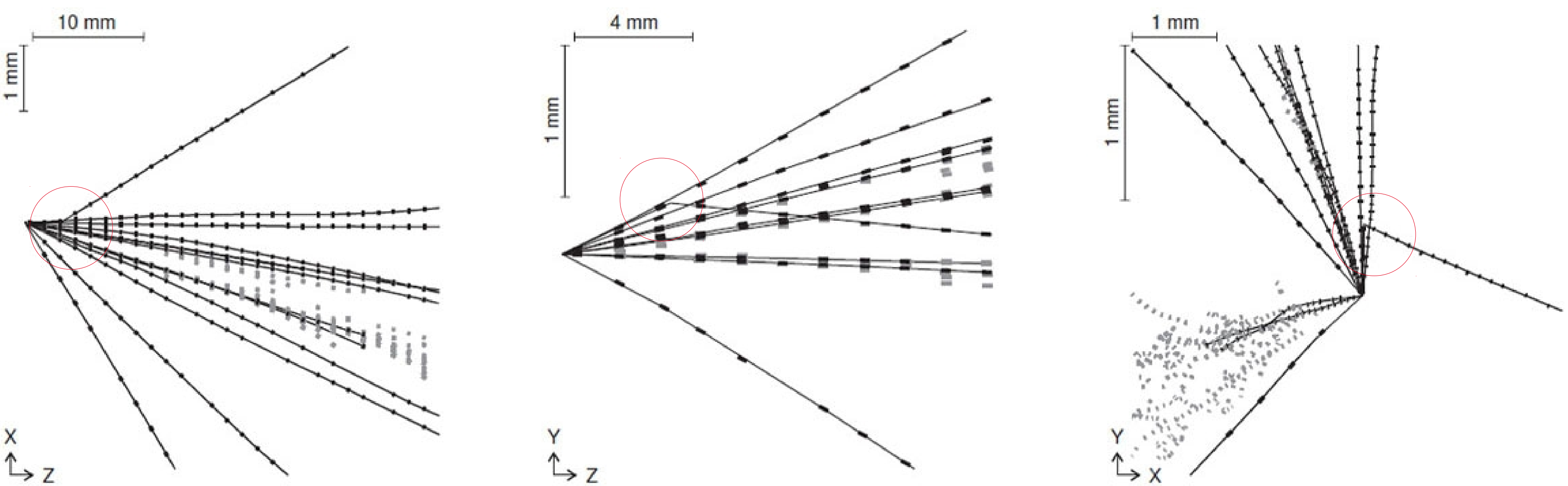
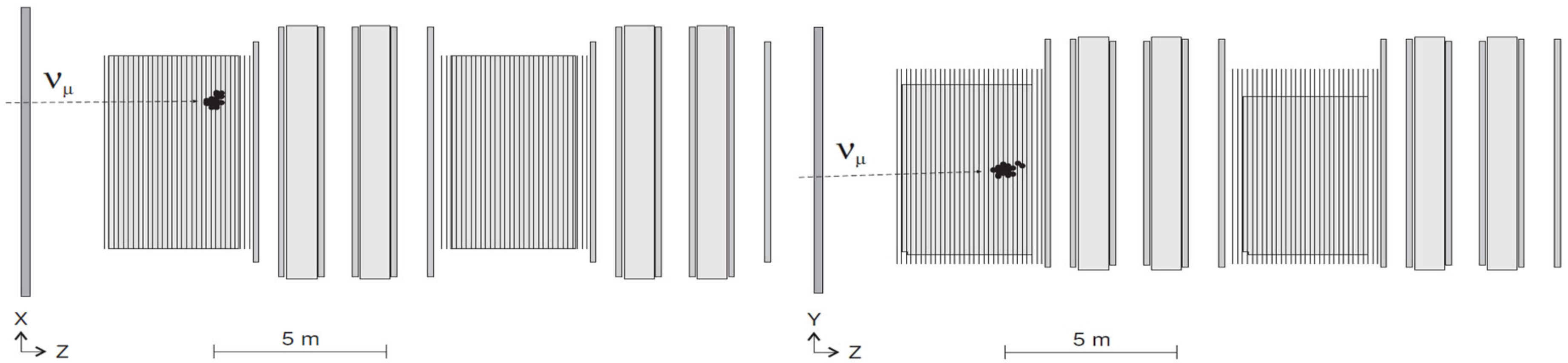
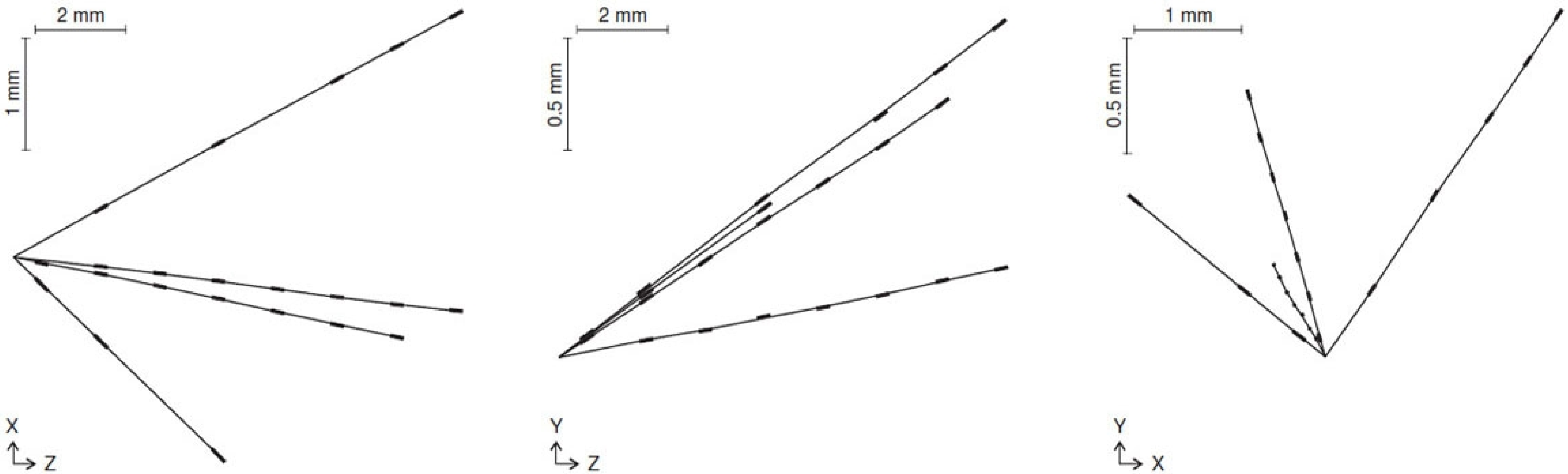
ν_μ charm event



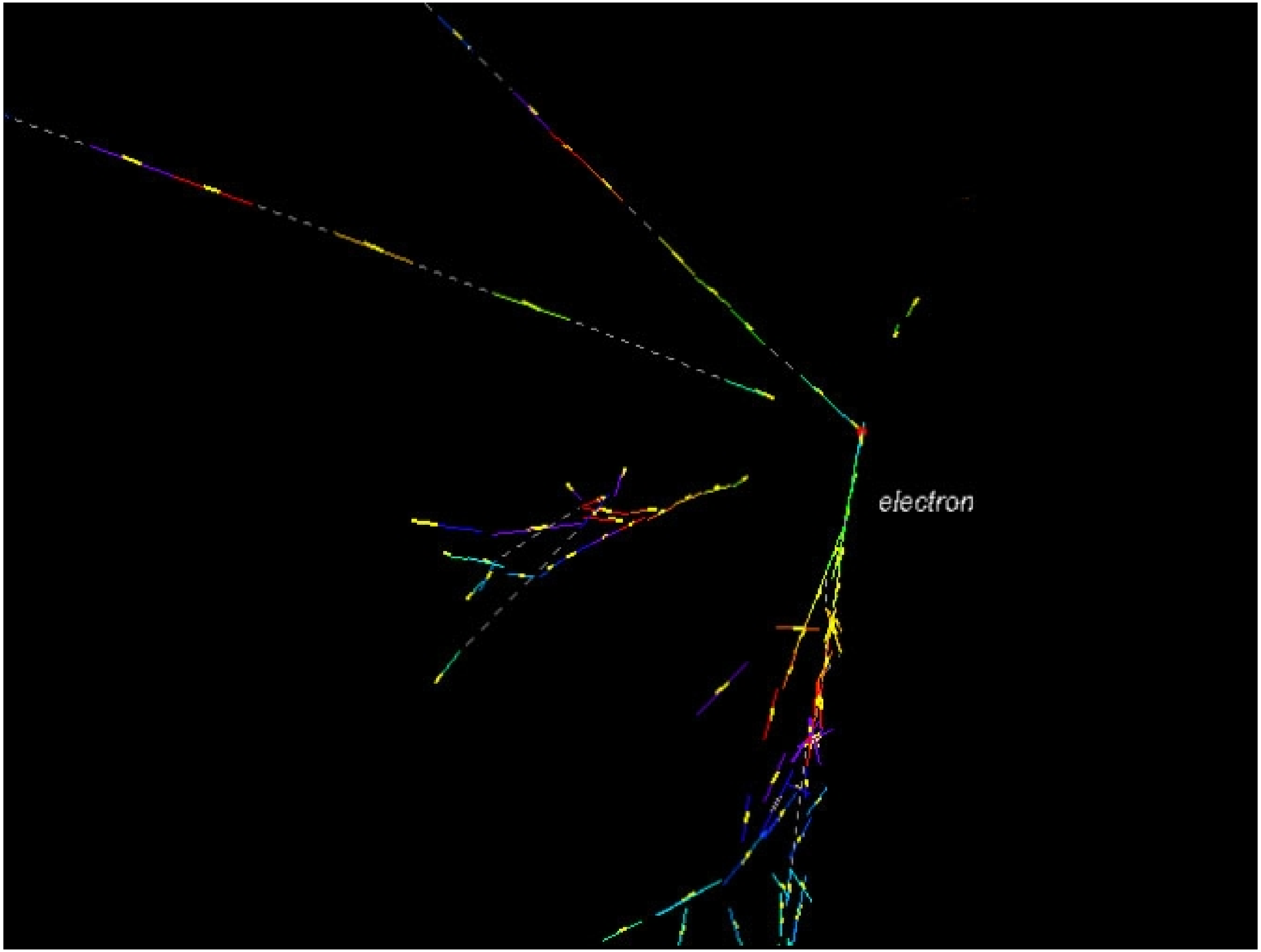


ν NC event





ν_e candidate



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systematic uncertainties

Systematic uncertainties	ns	Error distribution
Baseline (20 cm)	0.67	Gaussian
Decay point	0.2	Exponential (1 side)
Interaction point	2.0	Flat (1 side)
UTC delay	2.0	Gaussian
LNGS fibres	1.0	Gaussian
DAQ clock transmission	1.0	Gaussian
FPGA calibration	1.0	Gaussian
FWD trigger delay	1.0	Gaussian
CNGS-OPERA GPS synchronisation	1.7	Gaussian
MC simulation for TT timing	3.0	Gaussian
TT time response	2.3	Gaussian
BCT calibration	5.0	Gaussian
Total systematic uncertainty	**-5.9, +8.3**	

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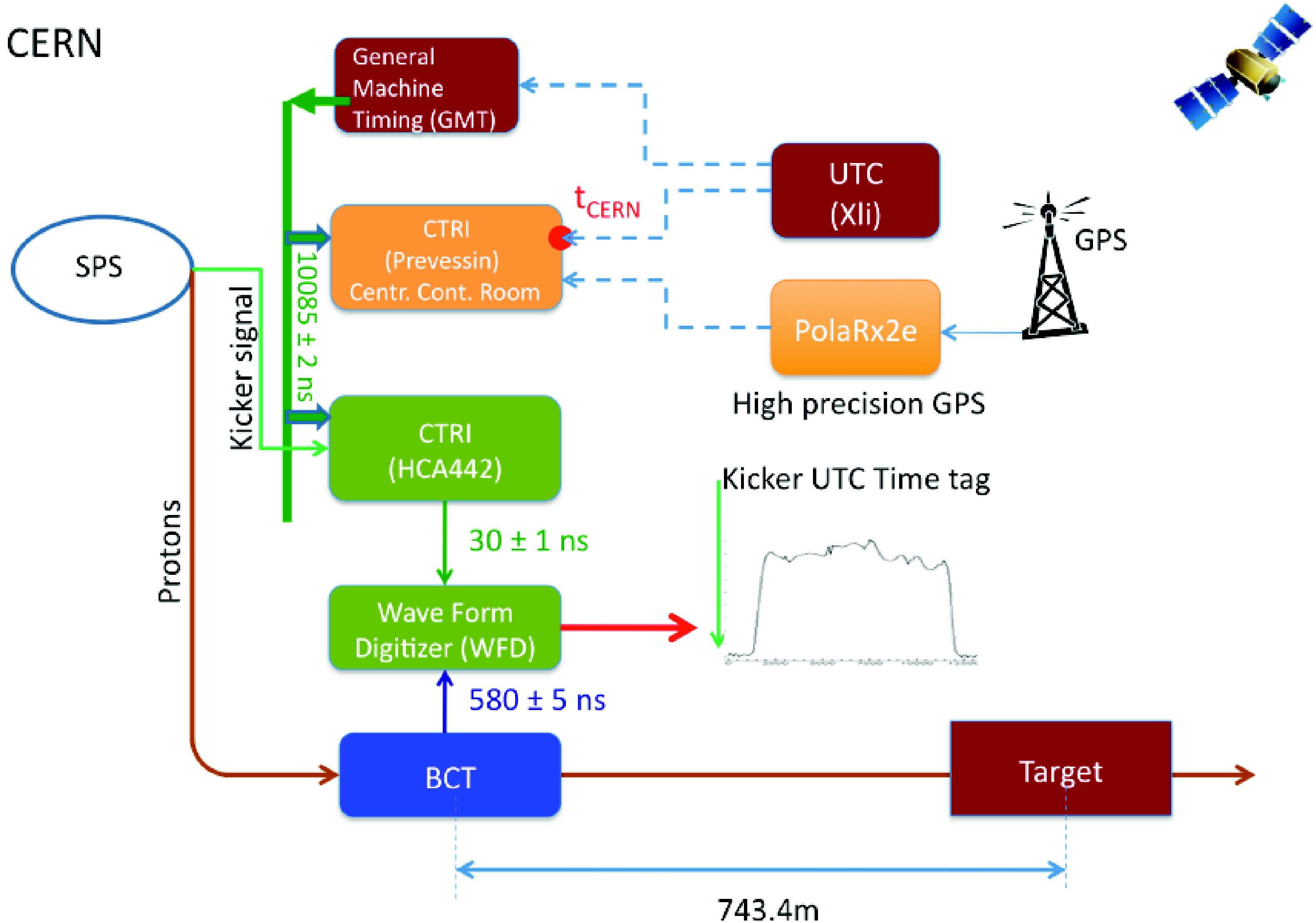
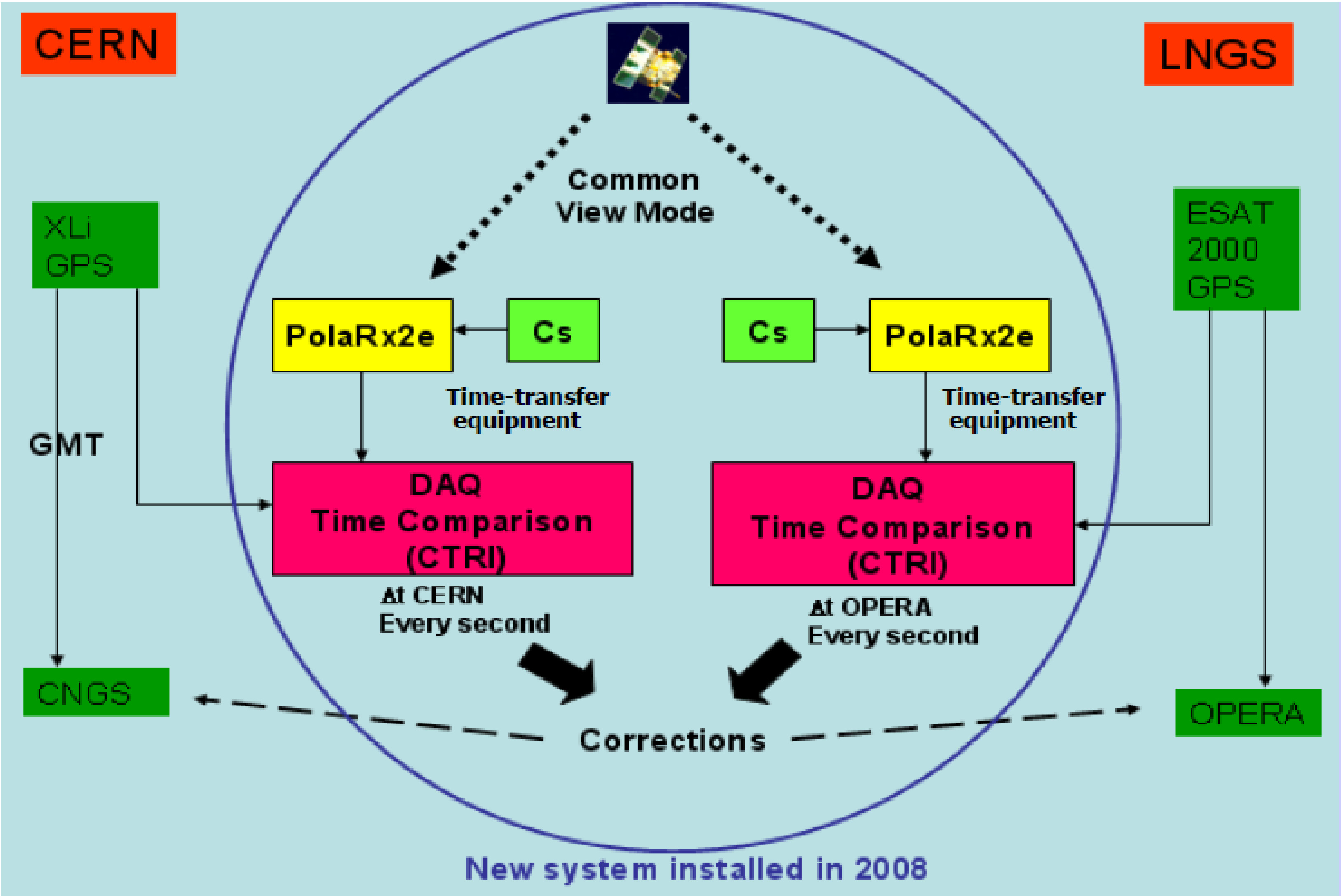
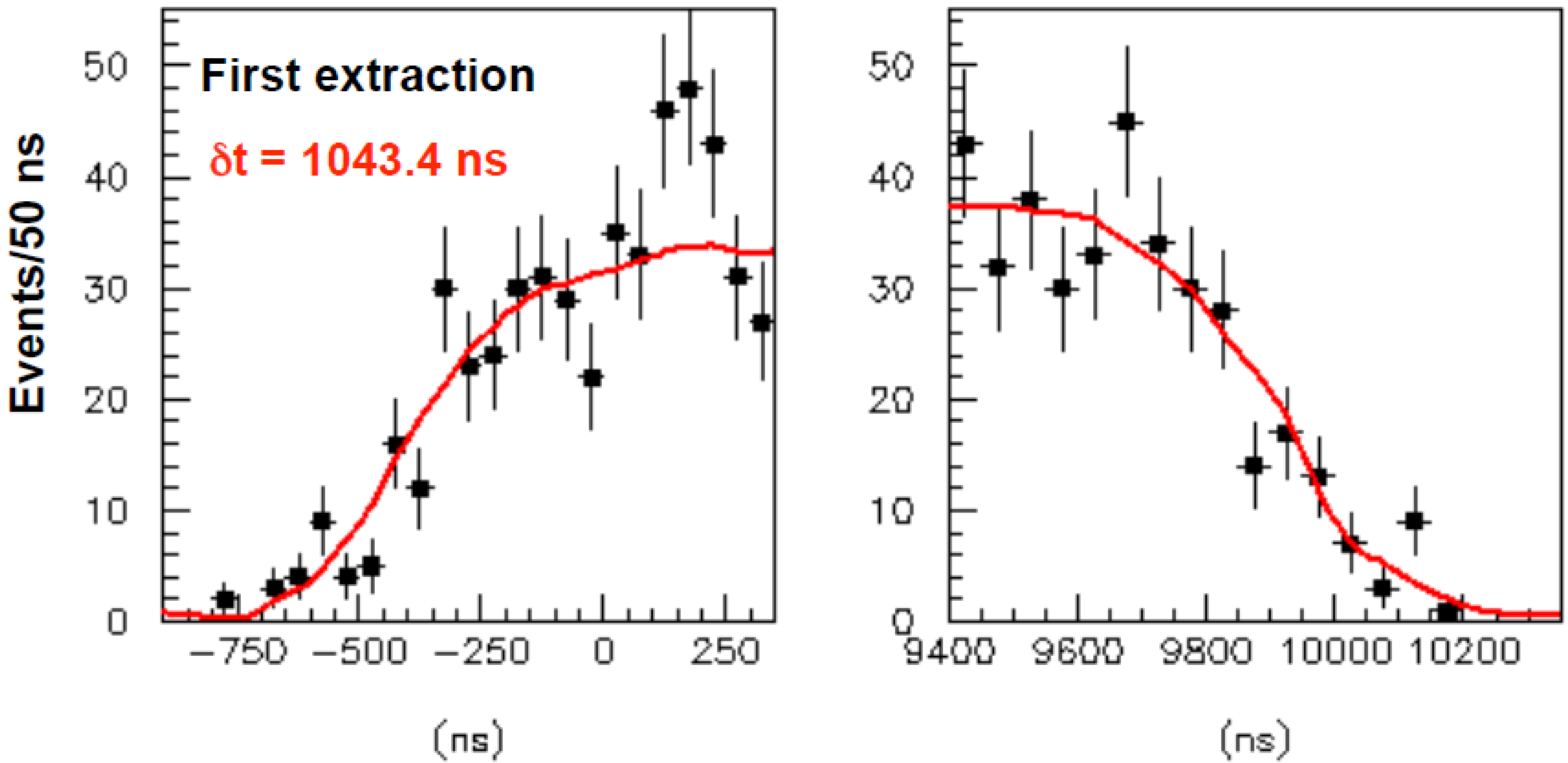
CERN timing



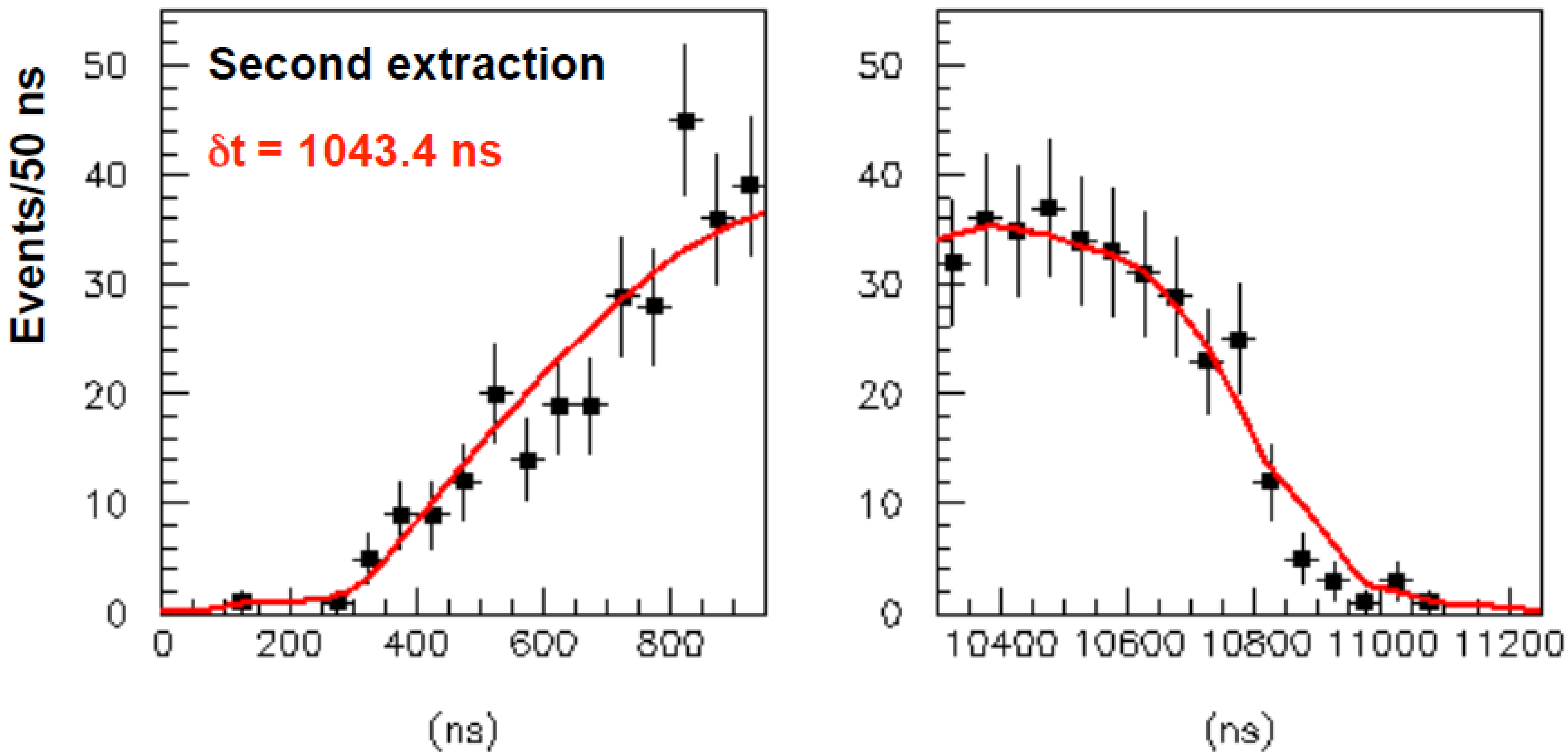
clock synchronization



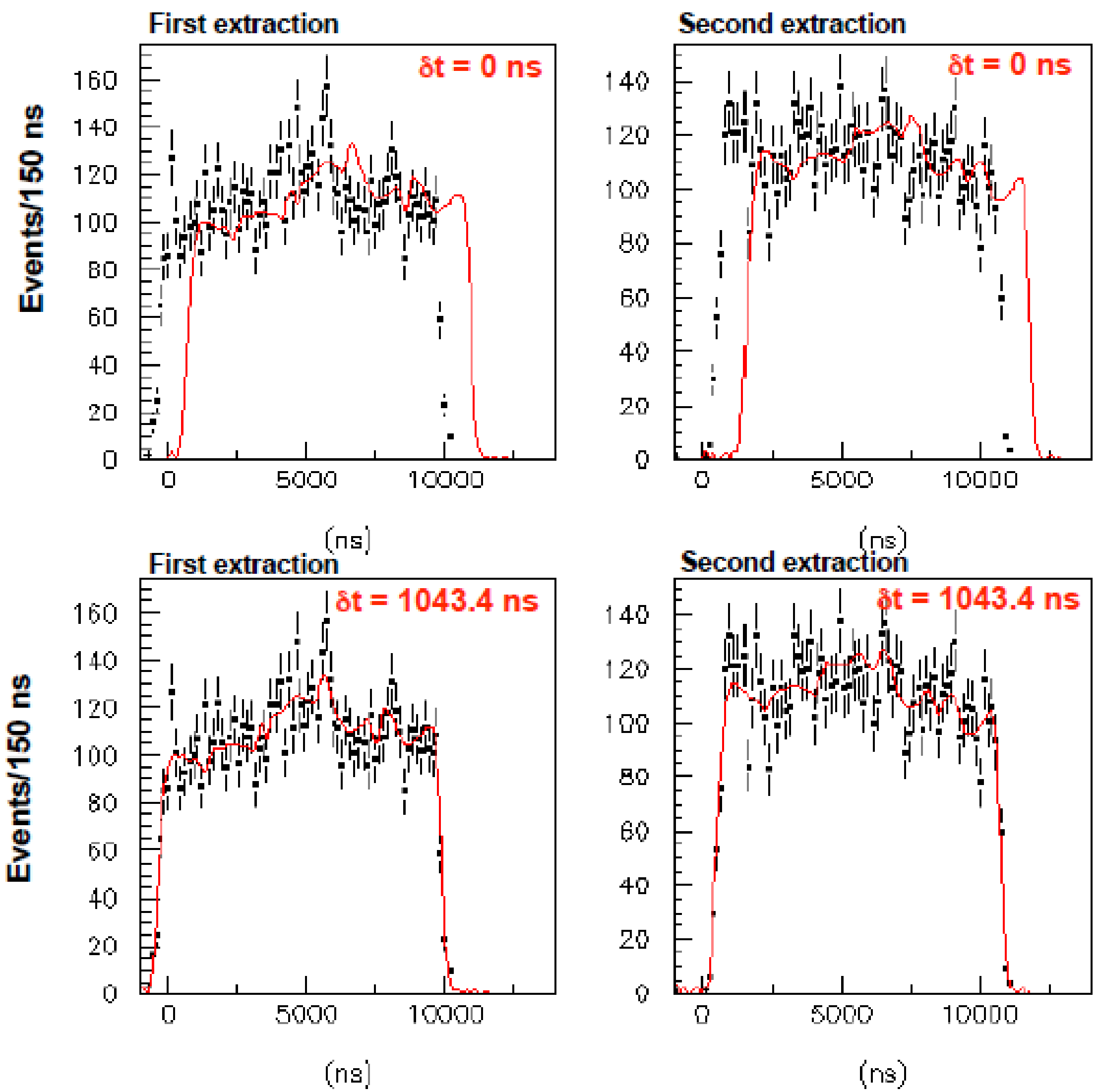
edges extraction 1



edges extraction 2



fit


First extraction
δt = 0 ns
Second extraction
δt = 0 ns
First extraction
δt = 1043.4 ns
Second extraction
δt = 1043.4 ns
Events/150 ns
Events/150 ns
(ns)
(ns)
(ns)
(ns)
0
5000
10000
160
140
120
100
80
60
40
20
0

first hit distribution

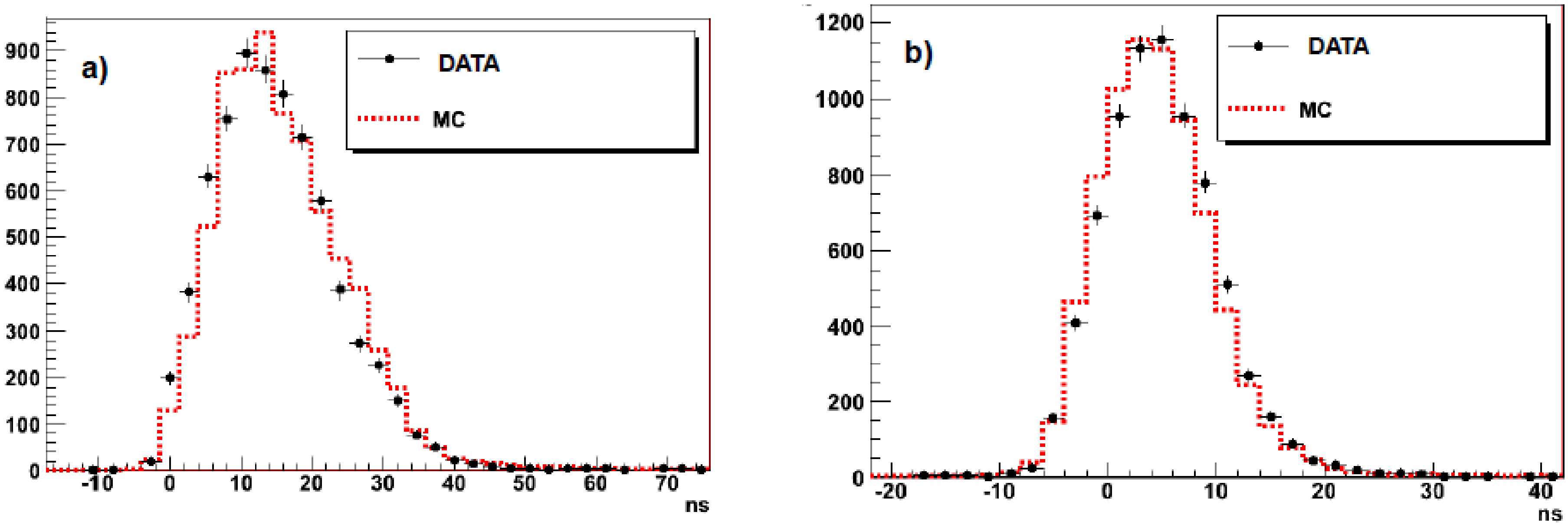


Fig. 9: Distribution of the time difference between the earliest TT hit and: a) the average time of the event, b) the average time of the muon track. Dots with error bars indicate data and the dotted line simulated events. Plot a) includes only internal events while plot b) only external events. The distributions are corrected for the longitudinal position of the hits.